VOLUME XXXII NUMBER 2

THE
JOURNAL OF GEOLOGY

February-March 1924

THE CONTRAST IN THE EFFECT OF GRANITE AND GABBRO INTRUSIONS ON THE ELY GREENSTONE

G. M. SCHWARTZ
Minnesota Geological Survey, Minneapolis, Minn.

ABSTRACT

The Vermilion iron district of northeastern Minnesota affords a valuable comparison of the contact effect of acid and basic rocks. The Ely greenstone consists of a body of hydrothermally altered and weathered basic flows and tuffs which show ellipsoidal, spherulitic, schistose, or massive structure. A compilation of the results of a study of many thin sections shows that the normal greenstone contains feldspar, chlorite, uralitic hornblende, magnetite, calcite, sericite, quartz, and many other minerals. Chlorite is the characteristic mineral.

Four granite masses intrude the greenstone, and at the contact a hornblende rock is developed. There is a gradation from normal greenstone to the hornblende rock, which is usually a schist. Compilation of the constituents of thin sections of the contact rock show that the important minerals are hornblende, plagioclase, magnetite, quartz, and titanite.

The Duluth gabbro intrudes the greenstone along the southeastern border of the Vermilion range. The greenstone at this contact has been recrystallized to a mosaic of rounded mineral grains. The abundant minerals are plagioclase, augite, hornblende, magnetite and lesser amounts of others. Augite is the characteristic mineral. Plagioclase has been entirely recrystallized forming fresh euhedral grains with clear twinning. This is in marked contrast with the feldspar of the granite contact rock which is clouded with alteration products.

Chemical analyses show little evidence of contribution from either the granite or gabbro. It is believed that the high temperature and relative dryness of basic as compared with granitic magmas is responsible for the marked difference in contact effects.

I. INTRODUCTION

The Vermilion iron district of northern Minnesota affords an unusual opportunity for the study of the effect of both granite and

gabbro intrusions on a basic igneous rock. The intruded rock is the Ely greenstone, a more or less dynamically and hydrothermally metamorphosed body of Archean basalt. There is a marked difference in the effect of the acid and basic intrusions on this basic material although each has a notable effect.

Aside from petrogenic interest there is an economic phase to the study as the Ely greenstone is closely related in occurrence and history to the Soudan iron formation in which the iron ores of the Vermilion range are found.

The data presented here are based on field observations by members of the Minnesota Geological Survey, including the writer, and more especially on a microscopic investigation supplemented by some necessary chemical data. Acknowledgments are due to Dr. W. H. Emmons, director of the Survey, for the opportunity to see the rocks and use the material on which the work is based. The work has been carried out under the supervision of Dr. F. F. Grout, whose interest and help are greatly appreciated.

II. PREVIOUS WORK ON THE CONTACT METAMORPHISM OF THE ELY GREENSTONE

The contact alteration of the Ely greenstone is mentioned repeatedly in the reports on northeastern Minnesota,[1] and there has been much confusion in its interpretation. The term "muscovadite"[2] was introduced for the granular rock along the gabbro

[1] N. H. Winchell, and others, *Geological and Natural History Survey of Minnesota, Annual Reports, First to Twenty-fourth, 1872–1892.* Especially A. Winchell, *ibid., Fifteenth Annual Report* (1886), pp. 171–202; Wadsworth, *ibid., Fifteenth Annual Report*, p. 354; N. H. Winchell, *ibid., Seventeenth Annual Report* (1888); W. S. Bayley, *ibid., Nineteenth Annual Report* (1889); *Journal of Geology*, Vols. I, II, III (1893–95); N. H. Winchell, *ibid., Twenty-first Annual Report* (1891), p. 143; U. S. Grant, *ibid., Twenty-second Annual Report* (1893); J. E. Spurr, *ibid., Twenty-second Annual Report* (1893); *Minn. Geol. and Nat. Hist. Survey Bull. 10* (1894); N. H. Winchell, *Final Report, The Geology of Minnesota*, Vol. IV (1899), Vol. V (1900). U. S. Grant, "Contact Metamorphism of a Basic Igneous Rock," *Geol. Soc. Am. Bull.*, Vol. XI (1900), pp. 503–10. J. M. Clements, "The Vermilion Iron-Bearing District of Minnesota," *U.S. Geol. Survey Mon. 45* (1903). C. R. Van Hise and C. K. Leith, "Geology of the Lake Superior Region," *U.S. Geol. Survey Mon. 52* (1911). C. Zapffe, "The Effect of a Basic Igneous Rock Intrusive on a Lake Superior Iron-Bearing Formation," *Econ. Geol.*, Vol. VII (1912), pp. 145–78.

[2] Derived from the Spanish word "muscovado" (brown sugar). Applied because of the brown granulated nature of the exposed rock.

contacts. These were described as altered greenstone, as altered sediments, and as a phase of the gabbro, etc., but the later work showed the muscovadite to represent a contact metamorphic phase of both greenstone and sediments.

The hornblende schists along the granite contact were at first thought to represent a separate formation called the Vermilion series, but Grant and Spurr[1] recognized them as greenstone altered by the granite. This interpretation has prevailed in the later reports.

III. THE ELY GREENSTONE WHERE UNAFFECTED BY INTRUSIVES

NAME AND GENERAL FEATURES

The name Ely greenstone was applied by Clements[2] to the greenish basic eruptive rocks of the Vermilion range on account of the well-developed character and good exposures of the formation in and near the city of Ely. This series of rocks, including the Soudan iron formation which is associated with the basic greenstone, had been originally termed the "Kawishiwin Series" by the Minnesota Geological Survey.[3] However, the United States Geological Survey considered it advisable to name the formations separately and introduced the terms Ely and Soudan.

As pointed out by Clements, the formation is not uniform and is not of exactly the same age throughout. Some rocks are effusive and some intrusive and others fragmental; but all are now much altered and have a green color, whence the name greenstone. The general nature of the greenstone has been described in the reports by Winchell and Clements, which are referred to above.

Due, in part, to original differences and more especially to the subsequent alteration which the formation has undergone, the greenstone is made up of a number of petrographic varieties, the chief being ellipsoidal, spherulitic, schistose, tuffaceous, siliceous, diabasic, etc.

[1] *Op. cit.*

[2] J. M. Clements, "The Vermilion Iron-Bearing District," *U.S. Geol. Survey Mon. 45* (1903), p. 131.

[3] N. H. Winchell, *Geol. and Nat. Hist. Survey of Minnesota, Final Report*, Vol. IV (1899), pp. 270–71.

DISTRIBUTION AND FIELD RELATIONS

Van Hise and Leith[1] have correlated the Ely greenstone with the greenstones of the other Lake Superior iron ranges. However,

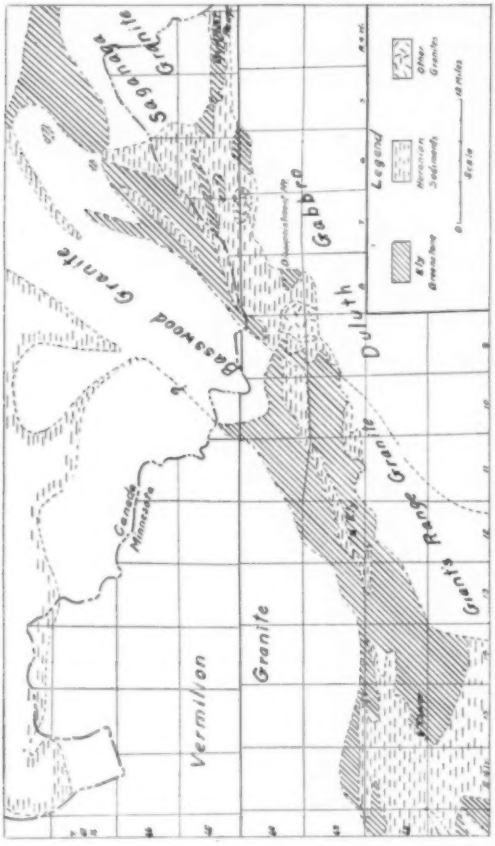

FIG. 1.—Sketch map of the Vermilion Iron Range, Minnesota and adjacent areas in Canada. Shows the relation of the granite masses and the Duluth gabbro to the Ely greenstone.

the use of the term Ely is confined to the Vermilion range and adjacent areas. It is with this restricted area that this paper is concerned. The general distribution of the Ely greenstone on the

[1] C. R. Van Hise and C. K. Leith, "Geology of the Lake Superior Region," *U.S. Geol. Survey Mon. 52* (1910), p. 122.

Vermilion range and its relation to other formations is shown in Figure 1.[1] The greenstone areas have been traced more or less continuously along the range for a length of 70 miles and a width of from 10 to 20 miles. The largest area, including the type locality, extends unbroken from Vermilion Lake to Moose Lake, a distance of 40 miles. The other large area is almost continuous with this and extends to the northeast on Hunter's Island, Canada. East of Moose Lake, Minnesota, the formation is less extensive and occurs as isolated areas in the Huronian sediments or in contact with gabbro and granite intrusives. The principal areas are at Disappointment Mountain, Knife Lake, from Twin Peaks to Gabemichigama Lake, and from Frog Rock Lake to the Gunflint range.

Outcrops are abundant throughout as the greenstone is, in general, the most resistant formation of the region and makes the high knobs and ridges. Specimens used in this study representing the various types of both the ordinary greenstone and the contact phases, are from every important area. Along the north side of the range the greenstone is in contact with the granites of Saganaga and Basswood lakes. On the south the area of greenstone near Vermilion Lake is bordered by Huronian sediments. To the east from Bearshead Lake to the Kawishiwi River south of Twin Lakes, the Giant's Range granite forms the southern boundary. The gabbro extends from this point east to Gunflint Lake.

Within the main area of greenstone is a more or less continuous belt of Huronian sediments extending from Vermilion Lake eastward, passing just north of Ely and on to Moose Lake, where the belt widens and the greenstone is found only as isolated patches beyond.

STRUCTURES AND TEXTURES

The original structures found are ellipsoidal, spherulitic, amygdaloidal, tuffaceous, and massive. Schistosity is common.

The amygdaloidal structure has been described[2] as the most common. This does not appear to be the case in the fifty specimens

[1] A more detailed map of the Vermilion range than Figure 1 may be found as Plate II, Monograph 45, and Plate VI, Monograph 52, of the U.S. Geol. Survey, and also in the atlas accompanying Monograph 45.

[2] C. R. Van Hise and C. K. Leith, *op. cit.*, p. 120.

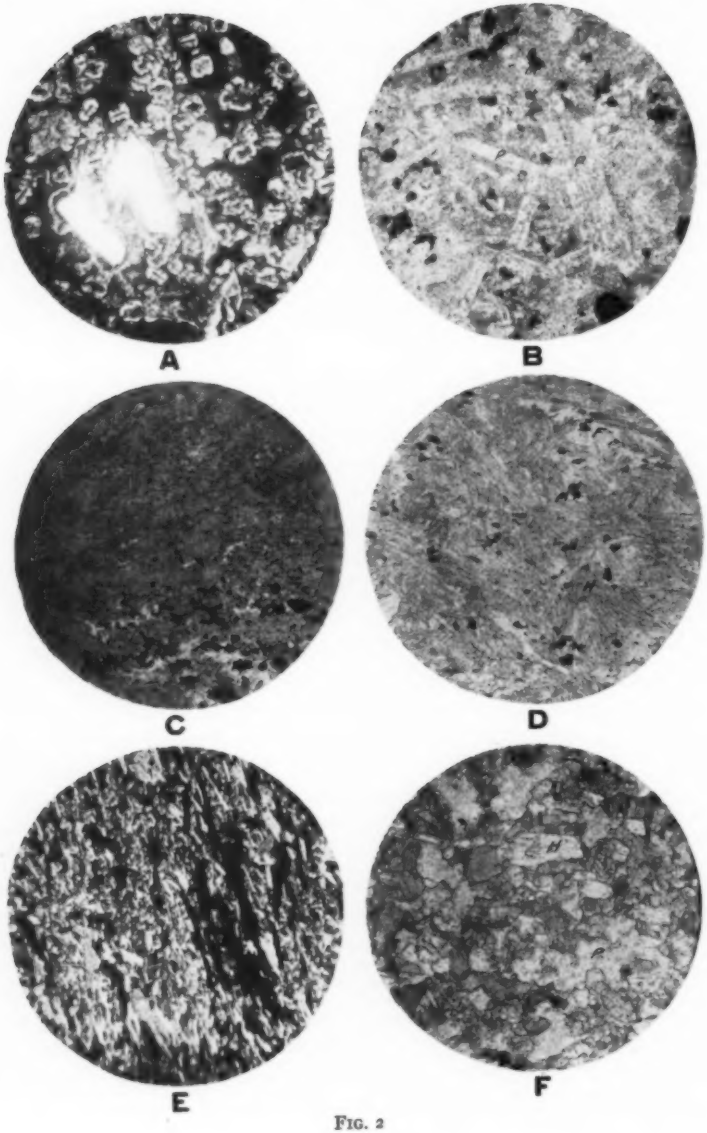

FIG. 2

EXPLANATION OF FIGURE 2

FIG. 2.—Photomicrographs of normal greenstones, and of hornblende rocks derived from greenstone by granite contact metamorphism.

A. Spherulitic greenstone. The spherulites are composed of hornblende and feldspar. Note the idiomorphic phenocrysts of feldspar. From Sec. 35, T. 65 N., R. 6 W., south of Ogishke Muncie Lake. Mag. ×43.

B. Greenstone with diabasic texture. Note the lath-shaped plagioclase (*P*) The black is magnetite (*M*). The confused nature aside from the magnetite and feldspar is typical of the normal greenstone. From NW. ¼ Sec. 28, T. 63 N., R. 11 W. Near Gordon Lake. Mag. ×43.

C. Ellipsoidal greenstone. Consists of a confused mass of chlorite, hornblende, and feldspar. The black grains are magnetite. From Disappointment Mountain. Compare with Figure 3, C. Mag. ×43.

D. Hornblende schist from an ellipsoidal greenstone outcrop about 1,000 feet from the granite contact. The fibrous grains are hornblende (*H*), and the dark patches are magnetite (*M*), and the clear areas feldspar (*F*). Compare with Figure 2, D and Figure 4, C. From the Portage from the Kawishiwi River to Twin Lakes. Mag. ×42.

E. Hornblende schist. Large grains of hornblende (*H*) with a fine mosaic of feldspar (*F*). From the near granite at the north end of White Iron Lake. Crossed nicols. Mag. ×43.

F. Hornblende rock. A granular aggregate of plagioclase (*P*) and hornblende (*H*), showing no schistosity. From near the granite at the south end of West Gull Lake. Mag. ×39.

examined, or on the outcrops visited by the writer. However, it is probable that amygdaloidal structure was more abundant in the original unaltered rock.

Spherulitic structure (Fig. 2, A) although not abundant, is found well developed in several places, notably in Sec. 21, T. 63 N., R. 12 W., on the north shore of Long Lake; Sec. 35, T. 65 N., R. 6 W., south of Ogishke Muncie Lake; and Sec. 17, T. 65 N., R. 5 W., north shore of Frog Rock Lake, southeast of Jasper Peak, and north of Twin Lakes. Spherulites are often found in combination with ellipsoidal structure.

Ellipsoidal structure in the greenstone is common and can be found in most large exposures in varying degrees of development and is the safest criterion for the recognition of the greenstone. The ellipsoids vary from less than an inch to 4 feet in diameter. The smallest noted show well in an ordinary hand specimen. The ellipsoids are, in some cases, amygdaloidal around the outside with a dense core and have a somewhat seamed and schistose matrix. Occasionally the ellipsoids are flattened to such an extent that a banded schist results. However, where the schist is developed by contact action a hornblende schist may result without essential distortion of the ellipsoids. The ellipsoids and matrix have been described in earlier reports as essentially similar, mineralogically, but this is not always true. Specimens were collected on the west edge of the city of Ely where recent blasting has exposed excellent fresh ellipsoidal greenstone. Sections were made from the dense core, the amygdaloidal rim of the ellipsoid, and the matrix. The chief difference is the high epidote of the matrix compared with the feldspathic core. The core, although much altered, retained a diabasic texture, the amygdaloidal rim showed a spherulitic texture, while the matrix contained a network of veins in apparently massive material. The core contained at least 50 per cent plagioclase, while the rim showed much less and the matrix practically none. Chlorite was especially abundant in the amygdaloidal portion and also averaged 20 to 25 per cent in the other parts. Epidote makes up fully 50 per cent of the matrix, whereas only traces appear in the core. Calcite is especially abundant in veins in the matrix. Considerable isotropic material is present in the amygdaloidal portion.

Chemical analysis might show that the composition is not far different for the various parts, but certainly the mineral composition and texture are very different. A similar contrast was noted in a specimen from Sec. 11, T. 62 N., R. 17 W., at the west end of Vermilion Lake. The core is green and contains much hornblende with minor chlorite, epidote, and plagioclase, whereas the matrix is 84 per cent epidote and the remainder mainly plagioclase with traces of hornblende, chlorite, and magnetite. Winchell[1] has described specimens not unlike those described above.

Much of the greenstone is massive and in many cases this shows a diabasic texture (Fig. 2, B). Tuffaceous greenstone is not commonly well developed, but some thin sections show a tuffaceous or fragmental nature. The best exposure of tuffaceous materials noted in the field was on the north shore of Knife Lake at the narrows in Section 24.

Well-developed greenstone schist is not common, but some tendency to part along certain planes may be found in most outcrops. The entire formation has been referred to as a schist, but it should be noted that normally the schistosity is only imperfectly developed.

The textures of the greenstone are diabasic and porphyritic and, while in many cases obscured by alteration to a confused aggregate (Fig. 2, C), can nevertheless be seen remarkably well considering the age of the rock.

Nineteen out of fifty thin sections of greenstone unaffected by contact action showed remnants of diabasic texture (Fig. 2, B). As many greenstones are so altered that all original textures have disappeared, probably over 50 per cent were once diabasic. Porphyritic texture with feldspars as phenocrysts is common and apparently indicates a slightly later intrusive phase of the greenstone. Phenocrysts of feldspar may occur in otherwise spherulitic greenstone as shown in Figure 2, A.

MINERALS OF THE NORMAL GREENSTONE

The minerals of the normal greenstone are largely secondary but some primary minerals remain. The most abundant minerals

[1] N. H. Winchell, *Geol. and Nat. Hist. Survey of Minnesota, Final Report*, Vol. V (1900), p. 750.

are: plagioclase, chlorite, hornblende, epidote, calcite, magnetite; those of lesser importance are leucoxene, quartz, actinolite, augite, sericite, kaolin, limonite, pyrite; while rare minerals are zoisite, biotite, bronzite, talc, apatite, titanite, perovskite, and ilmenite. Of these only plagioclase, augite, bronzite, quartz, magnetite, titanite, ilmenite, perovskite, and hornblende are believed to be primary. Some of these notably hornblende, are secondary as well.

An attempt was made to show the mineral composition graphically in Figures 8 and 9. A consideration of these diagrams brings out several points. Feldspar is an important constituent, appearing in all except possibly one greenstone, but the amount varies from 10 to 70 per cent. Pyroxene remains in only six out of forty-nine specimens. Hornblende is rather constantly present, often in considerable amount. Chlorite is even more often present and in considerable quantity. As a rule chlorite and hornblende are not present in large percentages in the same rock, which indicates that they are formed from the same primary minerals. Magnetite is usually present but, as a rule, in small amounts. Epidote, calcite, quartz, and leucoxene are present as small amounts in half or more of the specimens.

The feldspar present in the greenstone is normally plagioclase but, as a rule, it is so altered that further determination is impossible. In general it may be said that the feldspars of the greenstone show a great variety of alteration from incipient stages to the entire destruction of the original material, and that various minerals result, especially sericite, paragonite, kaolin, calcite, etc.

The presence of pyroxene in the greenstone is uncommon although the abundance of hornblende, epidote-zoisite, and chlorite indicates the presence of more pyroxene in the original rock.

Hornblende commonly occurs as secondary uralitic patches, in some cases clearly pseudomorphic after augite. It occurs as radial groups with feldspar in spherulites. In a few cases good crystals are abundant showing the cleavage and form of hornblende.

Chlorite is one of the most abundant and is the most characteristic mineral of the normal greenstone. As a rule it occurs as shreds and flakes although in some slides it is partly in areas whose dis-

tribution and outline suggest that it is pseudomorphic after augite. In one slide chlorite inclosed feldspar, while in another case alteration rims of chlorite surrounded pyroxene grains.

Magnetite is present in small amounts in about 60 per cent of the specimens, as a rule, in small grains or dustlike aggregates.

Quartz is a minor constituent and, as a rule, is clearly secondary. A common occurrence is as a mosaic with feldspars where alteration has been intense enough to destroy the original feldspar.

Leucoxene is also a minor constituent but is found in many slides as bunches of grayish material commonly associated with iron oxide.

The abundance of secondary calcite has been noted by Van Hise and Leith[1] as one of the conspicuous features of the formation. Figure 8 shows that it is present in a majority of greenstones. As a rule the amount does not exceed 10 per cent, but in a few slides amounts ranging up to 30 per cent were estimated by the writer. Calcite is one of the most abundant minerals found in the veins which cut the greenstone. This is especially true of the seamed matrix of the ellipsoids. However, most of the calcite is scattered throughout the rock where it must have been formed in part by the alteration of pre-existing minerals.

Calcite most commonly replaces, partially or almost completely, the lathlike forms of the feldspars. In other places it occurs with chlorite in areas which suggest original minerals such as augite. More rarely some of the ferromagnesian mineral remains. Less common, but significant, is the occurrence of calcite areas dotted with magnetite. Undoubtedly the derivation of calcite from augite and other similar minerals is less clearly shown, due to a more complete and early destruction of the basic minerals than of the feldspar. The lime in the calcite is probably derived from the destruction of lime minerals in the original rock. The CO_2 is probably introduced by hot water for the calcite is associated with sericite as shown in Figure 8. There are numerous intrusions of granite and gabbro, and dikes of various sorts which cut the greenstone, but no evidence was obtained as to which of these was the source of the hydrothermal solutions which furnished the carbon dioxide.

[1] C. R. Van Hise and C. K. Leith, *op. cit.*, p. 121.

CHEMICAL COMPOSITION OF THE GREENSTONE

The chemical composition of the greenstone unaffected by contact action is shown in the following table of analyses (Table I).

TABLE I

ANALYSES OF ELY GREENSTONE

	I	II	III	IV	V	VI	VII	VIII
SiO_2	51.73	51.95	60.61	52.94	43.96	50.47	49.65	48.23
Al_2O_3	15.28	12.58	16.61	14.70	16.03	18.48	16.36	18.12
Fe_2O_3	3.41	.90	1.97	2.52	10.50	2.13	4.39	2.88
FeO	7.30	8.77	5.09	7.80	8.74	7.74	7.19	8.46
MgO	6.72	8.90	3.10	4.49	6.56	6.90	8.00	6.28
CaO	9.40	7.00	4.46	6.56	9.54	6.61	9.18	9.23
Na_2O	3.83	2.79	3.11	3.09	1.62	2.58	2.49	2.80
K_2O	.76	1.38	.25	.04	.27	.30	1.17	.57
H_2O-	.00	.14	.....	.....	.....	.....	.....	.....
H_2O+	2.86	2.67	2.45	2.04	1.84	2.34	2.39	1.61
TiO_2	.78	1.03	.....	.....	.....	.....	.....	1.00
P_2O_5	.....	.....	.....	.....	.....	.....	.....	.12
CO_2	.....	1.02	1.57	4.86	.....	.....	.....	.39
C_2O_3	.....	.17	.....	.....	.....	.....	.....	.....
S	.....	.11	.....	.....	.....	.....	.....	.....
Mn	.15	.15	.....	.....	.....	.....	.....	.15
Ni	.....	.....	.....	.....	.....	.....	.....	.07
	102.22	99.56	99.22	99.04	99.06	97.52	100.82	100.00

*I. Average of three phases of greenstone at Ely. Analyst, S. Darling.

*II. Ely greenstone from Pine Island, Lake Vermilion. Analyst, S. Darling.

III. Interior of ellipsoid, Ely. *Minn. Geol. Survey, Twenty-third Annual Report*, p. 204. Analyst, C. F. Sidener.

IV. Tuffaceous greenstone, south shore Long Lake. *Minn. Geol. Survey, Twenty-third Annual Report*, p. 204. Analyst, C. F. Sidener.

V. Greenstone (Tuff), Kawasachong Falls. *Minn. Geol. Survey, Nineteenth Annual Report*, p. 126. Analyst, C. F. Sidener.

VI. Greenstone, NW. ¼ Sec. 4, T. 63 N., R. 9 W. *Minn. Geol. Survey, Nineteenth Annual Report*, p. 123. Analyst, C. F. Sidener.

VII. Greenstone, NW. ¼ SW. ¼ Sec. 17, T. 65 N., R. 5 W. *Minn. Geol. Survey, Final Report*, Vol. V, p. 519. Analysts, Dodge and Sidener.

VIII. Average of basic Keewatin rocks from Lake Superior region. Zapffe, *Econ. Geol.*, Vol. VII, p. 155.

* Published for the first time.

Numbers I and II are from composite samples selected in the field by Dr. F. F. Grout for the purpose of showing the general composition of the greenstone. Numbers III and V are the only ones showing an important difference in silica. Ferric iron with a

range from .90 to 10.50 is the only constituent to show a wide variation. The other variations are such as to emphasize the field and petrographic differences noted above.

AGE

The Ely greenstone was early considered to be the base of the Archean.[1] Lawson,[2] however, working for the Canadian geological survey in the Rainy Lake region, has described a metamorphosed sedimentary series termed the Coutchiching, lying below the Keewatin. Some question Lawson's interpretation, but all agree that the greenstone is Keewatin.

IV. THE GRANITES AND THEIR CONTACT EFFECTS ON THE ELY GREENSTONE

THE GRANITES—AGE, DISTRIBUTION, AND CHARACTER

There are four granites that intrude the Ely greenstone along the Vermilion range. Three of these are on the north side. They are, from east to west, the Saganaga, the Basswood, and the Vermilion granites. The Giant's Range granite forms the south border of the range from Bearshead Lake to Twin Lakes (Fig. 1). These granites have been described in the Minnesota Geological Survey reports,[3] and more recently by Clements,[4] and by Van Hise and Leith.[5]

The Saganaga granite has an area in Minnesota of 100 square miles. The age of this granite is unquestionably Laurentian as it intrudes and metamorphoses the Ely greenstone and pebbles from it are found in the Ogishke conglomerate which marks the base of the Huronian. Macroscopically the rock is coarse to porphyritic with quartz phenocrysts. The color varies from gray to pink and it is mainly a hornblende granite. The important minerals are plagio-

[1] N. H. Winchell, "The Oldest Rocks," *American Geologist*, Vol. XXVII (1888), p. 262. J. M. Clements, *op. cit.*, p. 33.

[2] A. C. Lawson, "The Geology of Rainy Lake"; *Report F, Geol. and Nat. Hist. Survey of Canada* (1888). "The Archean Geology of Rainy Lake Restudied," *Canada Department of Mines, Memoir 40* (1913).

[3] N. H. Winchell, and others, especially in *Geol. and Nat. Hist. Survey of Minnesota, Final Report*, Vols. IV, V.

[4] J. M. Clements, *op. cit.*, pp. 246–73; 352–72.

[5] C. R. Van Hise and C. K. Leith, *op. cit.*, pp. 118–37.

clase, orthoclase, quartz, hornblende, and mica. An analysis is given on page 105.

The Basswood and Vermilion granites extend in a continuous belt from the Saganaga mass westward. The dividing lines between the various masses have not been closely established as yet, but are indicated approximately in Figure 1.

These granites were all classified by Clements[1] and Van Hise and Leith[2] as Laurentian, but recent work by Grout[3] has shown that, for the most part, the Basswood and Vermilion granites are Algoman.

The Basswood granite has clearly intruded and metamorphosed the Ogishke and Knife Lake formations at the south end of Newfound Lake. This granite mass is clearly of later age than the Saganaga granite to the east and is a hornblende granite, whereas the Vermilion mass to the west is a biotite granite. Therefore, it is apparently a distinct intrusive and the term Basswood granite is introduced here to designate it. The texture of the granite varies from fine to coarse, and the color, which is usually pink, varies from light to dark. The minerals are plagioclase, orthoclase, hornblende, quartz, and biotite with considerable amounts of secondary minerals.

The Vermilion granite is, for the most part, a biotite granite with a light-pink color. It is unmetamorphosed in contrast with the Laurentian granite which is found locally associated with it. The abundant minerals are orthoclase, plagioclase, microcline, biotite, and quartz. An analysis is given on page 105.

The Giant's Range granite is found only on the south side of the Vermilion range. It is definitely Algoman in age, as it intrudes the Lower-Middle Huronian sediments, but pebbles of it appear in the conglomerate of the Upper Huronian. The granite for the most part is pink and porphyritic, although fine-grained phases are also abundant. It is a hornblende granite and as a rule essentially unaltered.

[1] J. M. Clements, *op. cit.*, p. 246.

[2] C. R. Van Hise, and C. K. Leith, *op. cit.*, p. 128.

[3] F. F. Grout, Bulletin of the Minnesota Survey in preparation.

EFFECT OF THE GRANITE ON GREENSTONE

THE HORNBLENDE ROCKS

Wherever the granites intrude the greenstone a hornblende rock is developed. This rock has been referred to in the literature as a hornblende schist and as a rule the schist structure is prominent but in some places the minerals are not oriented (Fig. 2, D). The width of the contact zone is variable. In some places within a few hundred feet of the granite, the greenstone is essentially unchanged; more rarely some change may be noted a mile from the contact. In most cases there is a gradation from the normal greenstone to the hornblende rock.

The larger features of the greenstone, such as ellipsoidal structure, are not necessarily destroyed as a result of the contact action so that ellipsoidal and massive, as well as schistose structures, are found, as for example on the portage from Twin Lakes to the Kawishiwi River and at White Iron Beach in Sec. 31, T. 63 N., R. 11 W. Thus it is indicated that the development of hornblende at the contact is not due primarily to movement.

Minerals of the hornblende rocks.—The list of minerals approximately in order of abundance, includes hornblende, plagioclase, magnetite, epidote, zoisite, quartz, titanite, chlorite, and actinolite, with minor amounts of sericite, kaolin, leucoxene, olivine, biotite, orthoclase, apatite, pyrite, limonite, and garnet. Figures 8 and 10 show graphically the important minerals for comparison with other phases of the greenstone.

The feldspar is probably always plagioclase unless granitic material has worked into the rock, which is uncommon except in inclusions. The feldspar rarely shows euhedral form or twinning and is, as a rule, more or less clouded with alteration products The usual texture of the feldspar is a mosaic which fills in around the hornblende crystals (Fig. 2, E). In rare cases remnants of diabasic texture remain.

Hornblende composes from 10 to 95 per cent of these rocks. The specimen with the greatest amount of hornblende, having only a trace of magnetite in addition, was analyzed after removal of the magnetite. The composition is given on page 105. It is much the

same as the analyzed hornblende schists from near the granite and the normal greenstone as well; which shows that it is chemically possible for the greenstone to recrystallize to a rock almost entirely hornblende. All of the hornblende is the common green variety and varies in size of grain from uralite shreds to grains a centimeter long. Near the contact the euhedral or subhedral grains are found and these are normally of increasing size as the granite is approached. Specimens from the core of ellipsoids which have altered to hornblende schist show very small grains of hornblende compared to the other phases of the greenstone which occur equally near the contact.

Magnetite is a common, though not abundant, mineral near the granite, but if anything it is less abundant than in the normal greenstone. It normally forms small irregular grains.

Titanite is present in small amounts in half of the slides examined and its formation from the leucoxene of the greenstone is indicated by the decrease in that mineral from the amount in the normal greenstone.

Quartz is common in small amounts, occurring as a rule in a fine mosaic with the feldspar. Apparently it is not easily incorporated into the hornblende by recrystallization as are most of the alteration products. Sericite and kaolin persist in the feldspar as a rule almost to the contact. Pyroxene and olivine are very rare. Chlorite, epidote, and calcite, which are characteristic secondary minerals of the normal greenstone, are comparatively unimportant in the hornblende rock. The large development of hornblende is undoubtedly due, in part, to the recrystallization of the material in those minerals.

Chemical composition of the hornblende rocks.—The chemical composition of the hornblende schists, formed from greenstone by granite contact metamorphism is shown in the analyses given in Table II. A comparison of these analyses with those of the normal greenstone given on page 100 shows that there is no marked difference and there is no tendency of the hornblende rocks to approach the granite in composition. Alumina and magnesia show the only large difference. It is especially noteworthy that the alkalies are no higher in the hornblende schists than in the normal greenstone. It seems conclusive that the change from greenstone to a horn-

blende rock is not the result of the contribution of material from the granite, but of the recrystallization of the constituents of the original rock.

TABLE II

ANALYSES OF GRANITES AND THE ELY GREENSTONE, ALTERED TO HORNBLENDE SCHIST BY THE GRANITES

	1	2	3	4	5	6	7
SiO_2	69.34	72.06	51.53	46.22	47.50	48.01	48.25
Al_2O_3	17.25	16.00	10.61	14.24	17.03	8.34	8.38
Fe_2O_3	2.46	.45	2.98	3.93	4.15	2.29	2.13
FeO		.72	9.93	11.62	6.67	10.85	10.53
MgO	1.18	.97	8.74	7.40	6.70	16.84	16.93
CaO	3.43	.86	9.97	11.28	14.90	9.86	9.91
Na_2O	4.33	4.56	2.62	2.48	.76	.98	.98
K_2O	.71	3.54	.91	.81	.76	.37	.37
H_2O-	1.17	.05	.08	.28	.88	.10	.10
H_2O+		.39	.67	.05	.12	.40	.40
TiO_2	.....	.12	.60	1.70	.58	.46	.46
P_2O_5	.....	.09	.24	.15	.07	.12	.12
CO_2	.....	.10	.57	.....	.....	none	none
FeS_2	.....	.09	.29	(S) .06	(S) .03	.02	.02
MnO	.....	.06	.32	.02	.15	.25	.25
ZrO_2	.....	.03	.01	(Cl) .08	(SrO) .02 (Cl) .09	tr.	tr.
Cr_2O_3	.....	.02	.09	.01	.04	.22	.22
BaO	.....	.12	.....	.....	.....	.....	.....
	99.87	100.24	100.16	100.39	100.45	99.21	99.05

1. Saganaga granite (with hornblende) SW. ¼ NE. ¼ Sec. 22, T. 66 N., R. 5 W. *Minn. Geol. and Nat. Hist. Survey, Final Report*, Vol. V, p. 315. Analyst, A. D. Meeds.

*2. Vermilion granite, south of Pelican Lake. Analyst, F. F. Grout.

*3. Greenstone altered by granite (hornblende schist), northeast of Paulson mine, Gunflint range. Analyst, F. F. Grout.

4. Ellipsoidal greenstone schist near granite, Rainy Lake. Lawson, *Memoir 40, Can. Geol. Survey*, p. 50. Analyst, M. F. Connor.

5. Greenstone altered to hornblende schist, Rainy Lake. Lawson, *Memoir 40, Can. Geol. Survey*, p. 50. Analyst, M. F. Connor.

*6. Greenstone altered by granite. Nearly all hornblende. Near ¼ Cor. Sec. 20 and 21, T. 65 N., R. 4 W. Analysts, F. F. Grout and R. W. Gannett.

*7. Hornblende of No. 6, with magnetite .55 per cent removed.

* Published here for the first time.

Gradation from greenstone to hornblende rock.—The changes from normal greenstone to hornblende rock at the granite contact may be traced in several places. Two gradations are described below.

The first series consisting of eight specimens represents the greenstone from Frog Rock Lake to the contact with the Saganaga

granite at West Gull Lake, T. 65 N., R. 5 W. The first three specimens are from the north shore of Frog Rock Lake, all 2,500 feet or more from the granite. They represent schistose, diabasic, and spherulitic phases of essentially normal greenstone.

At approximately 1,000 feet from the contact the rock has remnants of diabasic texture and consists mostly of plagioclase and euhedral grains of hornblende with small amounts of other minerals.

About 100 feet from the main granite contact the altered greenstone consists of hornblende with lesser plagioclase and minor amounts of other minerals. The hornblende is distinctly euhedral and the plagioclase much clouded with sericite and kaolin.

Six inches from the contact the greenstone is schistose, and high in hornblende, which occurs as euhedral grains. Feldspar with sericite and kaolin, and traces of leucoxene are present.

In direct contact with the granite the greenstone has a granular texture but is similar in mineral composition to that farther away.

An inclusion in the granite from the same outcrop contains more feldspar than hornblende. The feldspar is in large grains much clouded with alteration products, but shows twinning in some grains. This suggests recrystallization and possibly some contribution from the granite, which probably also accounts for the increased amount of feldspar compared to hornblende.

A similar gradation may be seen along the portage from Twin Lakes to the Kawishiwi River. All of these rocks show at least slight effects of high temperature. At 2,500 feet and 1,500 feet from the granite the greenstones are of the normal type. They are schistose and consist essentially of hornblende and plagioclase in about equal amounts. Magnetite and titanite are accessory minerals and sericite and kaolin are found as alteration products in the feldspars. The rocks show fractures along which the minerals have turned entirely to hornblende. Inasmuch as there is no evidence of contributions from the granite at this distance, it is probable that the more severe effect along the fractures facilitated recrystallization of the rock to hornblende. At 1,000 feet from the granite the greenstone is ellipsoidal on the outcrop, but it is a hornblende schist (Fig. 2, D) notwithstanding the fact that the ellipsoids were hardly at all distorted. The rock is fully 60 per cent horn-

blende, which occurs as unusually small euhedral and oriented crystals. The remainder is feldspar, magnetite, and titanite. The feldspar is in the form of a mosaic, but is relatively free from alteration products, indicating that it has recrystallized.

The contact is not sharp at this exposure, but is a mixture of granite and greenstone for several feet; the granite part is largely feldspar and the greenstone mostly hornblende.

Inclusions in the granite at some places developed into a hornblendite with 85 per cent hornblende, and small amounts of feldspar, titanite, and magnetite. These inclusions will be referred to later.

The gradation described above shows a greater increase in hornblende near the contact than the series at Frog Rock Lake. It is noteworthy that chlorite, a characteristic mineral of the normal greenstone, is not found in any of this series of specimens. Chlorite evidently disappears with the first contact effects, being replaced by hornblende. The hornblende is more abundant and more nearly euhedral as the contact is approached, until it becomes so abundant that the grains interfere. Titanite replaces leucoxene, but sericite and kaolin persist at places up to the contact.

N. H. Winchell[1] has noted a similar gradation from Long Lake to Burntside Lake.

OTHER EFFECTS AT THE GRANITE CONTACT

Hornblendite inclusions or breccias in the granite are found at many places along the granite-greenstone contact as at the portage from Kawishiwi River to Twin Lakes. There is not in many places a complete gradation in texture and mineral composition from the greenstone at the contact to the hornblendite inclusions and the question of the origin of these inclusions presents itself. They apparently represent either greenstone recrystallized almost entirely to coarse hornblendite; or, as a basic border phase is present along some of the granites of the region, the inclusions may be a part of this border phase broken up and included in the granite.

Evidence regarding the origin is seen southeast of White Iron Beach, in Sec. 31, T. 63 N., R. 11 W. At this point the breccia

[1] N. H. Winchell, *Geol. and Nat. Hist. Survey of Minnesota, Final Report*, Vol. IV (1898), p. 258.

is made up of hornblendite fragments, the largest being about 2 inches in diameter. The breccia has, for the most part, been formed by granite having worked into the greenstone; and the same outcrop shows a gradation to hornblende schist free from granite. Thus it was concluded that the hornblendite inclusions represent recrystallized greenstone.

Hornblendite inclusions surrounded by a biotite granite gneiss were found by Dr. Grout south of Johnson Lake in the Vermilion granite. Apparently the gneiss represents a mixture of granite and hornblendite formed by the granite soaking in and reacting with the hornblendite. The outlines are definite and thus show the form of the original inclusions. The inner hornblendite inclusions consist of about 80 per cent hornblende with small amounts of plagioclase and biotite, and traces of sericite and apatite. Immediately surrounding the inclusions, the gneiss is composed of equal parts of granite and hornblendite. Farther from the hornblendite the gneiss contains feldspar, hornblende, and biotite. Near the contact of the gneiss with the granite the gneiss is largely feldspar and biotite. The granite surrounding the gneiss is practically the normal biotite granite. The changes are indicated graphically in Figure 3.

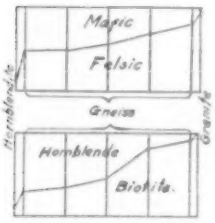

FIG. 3.—Changes in proportional amounts of the constituents in the transition gneiss between amphibolite inclusions and granite, Johnson Lake, Minnesota.

This would appear to be an example of the alteration of inclusions according to the reaction series as recently stated by Bowen.[1] It seems clear that in this case hornblende was converted to biotite by soaking in the biotite granite. This was not observed in the other masses which are hornblende granites. It should be emphasized that the first effect of the biotite granite was to convert the greenstone into a hornblende rock and biotite developed only where the inclusions and the granite had been most intimately mixed.

[1] N. L. Bowen, "The Behavior of Inclusions in Igneous Magmas," *Journal of Geology*, Vol. XXX (1922), pp. 513–67.

COMPARISON WITH OTHER DISTRICTS

A search was made through the descriptions of other districts to see if the alteration of basic rocks to hornblende schists by granite was characteristic of such contacts.

The Land's End (3)[1] granite intruded greenstone and sediments. Allport says, "Certain portions of these metamorphosed dolerites are, in fact, half-formed hornblende schists, which require only the addition of foliation to render the transformation complete." In the summary it is noted that augite and diallage are converted to a hornblendic substance, and that the alteration is a result of internal action, decomposition, and recrystallization, but not to contribution from the granite.

Teall (5) referring to the effect of the Cornwall granite on basic rocks, notes the replacement of augite by hornblende and that the feldspar is usually turbid. Mosaic texture is common.

Beck (7) has described a diabase altered by granite in the region southwest of Dresden. The rocks are now amphibolites and amphibolite schists. Hornblende is the abundant constituent; others are augite, plagioclase, biotite, titaniferous magnetite, apatite, rutile, epidote, and calcite. Feldspar forms a mosaic.

A similar case is described in the Elbthalgebirge (9). The altered diabase consists of a granular, green mass containing hornblende and other minerals. Diabase tuffs are also described as altered to actinolite and hornblende schists. Plagioclase and quartz form a mosaic.

Harker and Marr (8, 11) have given an unusually complete description of the effect of the Shap granite on basic lavas. The first signs of metamorphism are at from 1,120 to 1,200 yards from the granite. Brown mica or hornblende with small crystals of sphene occur in streaks. Due to the high lime content, hornblende is more common than mica in the body of the rock. The foregoing minerals seem to have formed largely from the alteration products. The feldspar, in so far as it has escaped alteration or incorporation into other minerals, occurs as a mosaic.

Sollas (15) has described xenoliths of gabbro in a granophyr in Ireland. The xenoliths consist of augite, biotite, magnetite, and

[1] Numbers in parentheses refer to the Bibliography.

lath-shaped plagioclase. In some inclusions, hornblende takes the place of the other ferromagnesian minerals.

Harker (19) described the alteration of gabbro fragments in a granophyr on the Isle of Skye. The gabbro has been more or less completely changed. Augite has altered on the outside to hornblende, in some cases almost completely, but still retaining characteristic striations. Diallage, enstatite, and hypersthene all show more or less alteration to hornblende. Magnetite is apparently increased. Other xenoliths have become granular aggregates of hornblende and are believed to represent altered basalt, as similar cases were found at Rum, Mull, and Ardnamurchan.

Parkinson (21) has described the effect of a granite on a diabase at Sorel Point, northern Jersey, England. Augite of the original rock is replaced by biotite and hornblende, the biotite is often associated with the hornblende in a manner that suggests its formation from that mineral.

Busz (22) has described the effect of a granophyre dike, on inclusions of gabbro at Ardnamurchan, Scotland. Plagioclase xenoliths (anorthite) have altered to orthoclase on the outside and augite to green or brownish green hornblende, biotite, and granular augite. Rhombic pyroxene changes to steatite with the excretion of magnetite.

Barrell (23) noted the uralitization of augite and of original hornblende in the contact alteration of a hornblende-andesite porphyry by a granite.

Kynaston made an unusually complete study of the effect of the Cheviot granite (24) on fresh enstatite-andesite. The most conspicuous change was the development of brown mica from pyroxene. Near the contact secondary pyroxene was also developed. The list of minerals produced by the contact action is pyroxene, biotite, quartz, orthoclase, plagioclase, amphibole, magnetite, and sphene.

Smith and Calkins (25) noted the formation of a fine-grained amphibolite from a fresh amygdaloidal basalt by the contact action of a granodiorite in the Cascade Range.

The change of a diabase at the contact with granite from near Harburg, has been described by Erdmannsdörfer (26). The feld-

spar changed chiefly in texture, forming a mosaic. The augite altered to hornblende or a mixture of diopside, biotite, and iron oxide. The alteration of the amygdules when filled mainly with chlorite resulted in the formation of hornblende. When calcite was also present, augite, biotite, and prehnite were formed.

Harker (27) noted the formation of fibrous hornblende and biotite in basalts altered by the granites of Skye, also the development of feldspar from the zeolites in the amygdules.

Reid and Flett (30) found greenstones altered to a hornfels near a granite contact in the Land's End district. Hornblende, augite, biotite, magnetite, sphene, and apatite were usually formed.

Collins (34) described the transition of a chlorite schist into a hornblende schist near the Laurentian granite contact in the Gowganda district of Canada. Immediately at the contact the final product was a coarse gneiss consisting of hornblende, feldspar, quartz, magnetite, and titanite.

Weigel (35) has described the alteration of diabase by granite in connection with contact metamorphic ore deposits in Eastern Siberia on the Japanese Sea. At the contact the diabase is coarser, the feldspar occurs in a mosaic and is believed to be acid; hornblende is more abundant. Many chemical analyses are given which tend to show that the altered diabase contains more SiO_2, Na_2O, P_2O_5, and less FeO, MgO, and CaO, while Al_2O_3, K_2O, TiO_2, and MnO are nearly constant. Very close to the contact biotite tends to form from augite and hornblende.

Rinne (37) describes diabase altered by acid intrusive rocks, forming hornblende schists. He states that many so-called amphibolites are the result of alteration by granite.

Several points of similarity are to be found between the alterations described above for basic rocks at granite contacts and those of the Ely greenstone. The original metamorphosed condition of the Ely greenstone naturally introduced factors not present in many of the other cases. Hornblende is mentioned throughout as one of the conspicuous minerals developed and hornblende schists and hornblendites analogous to those in Minnesota have been described. Feldspar commonly occurs as a mosaic, and this is characteristic of the granite contact rocks described in this paper.

The disappearance of chlorite has been noted by some of the investigators. The most characteristic change described in the literature which is not found at most of the contacts of granite with greenstone in Minnesota is the development of biotite. This was found in notable amounts only around the hornblendite inclusions at Johnson's Lake. In general, it may be said that the changes described for the Ely greenstone at granite contacts are more or less characteristic of those found in other parts of the world, but biotite develops only near the biotite granites.

V. THE DULUTH GABBRO AND ITS EFFECT ON THE ELY GREENSTONE

THE DULUTH GABBRO

The great gabbro mass of the Lake Superior region received its name because of the exposures at Duluth where it forms the heights along the north shore. The gabbro has been described in detail in the older publications of the Minnesota and United States Geological Surveys heretofore noted, as well as in current periodicals. Winchell[1] has summarized this early work. Recently the gabbro has been investigated by Grout.[2]

The Duluth gabbro is a laccolith, or a lopolith, as termed by Grout,[3] and is Keweenawan in age. It covers a great area about 130 miles long and 30 miles wide at its widest point, and extends from Duluth north and eastward in a broad curve to a point about 20 miles northeast of Grand Marais.

The average gabbro is medium to coarse, granitoid to ophitic in texture. The important minerals are plagioclase, augite, olivine, and magnetite. The plagioclase is normally about basic labradorite. Grout gives the varieties as normal gabbro, olivine gabbro, troctolite, peridotite, magnetite gabbro, and anorthosite. Many analyses of the gabbro and its various phases are available and five typical

[1] A. N. Winchell, "Review of the Nomenclature of Keweenawan Igneous Rocks," *Journal of Geology*, Vol. XVI (1908), pp. 765–74.

[2] F. F. Grout, "A Type of Igneous Differentiation," *Journal of Geology*, Vol. XXVI (1918), pp. 626–58.

[3] F. F. Grout, "The Lopolith," *American Journal of Science*, Vol. XLVI (1918), p. 516.

ones are given in Table III for comparison with the altered greenstone along the gabbro contact.

TABLE III

TYPICAL ANALYSES OF THE DULUTH GABBRO

	1	2	3	4	5
SiO_2	48.20	35.81	45.66	46.45	47.70
Al_2O_3	19.53	14.32	16.44	21.30	19.04
Fe_2O_3	Tr.	7.38	.66	.81	.87
FeO	10.60	15.25	13.90	9.57	8.84
MgO	9.28	10.49	11.57	7.90	8.65
CaO	8.51	7.23	7.23	9.83	8.96
Na_2O	2.52	2.06	2.13	2.14	2.53
K_2O	.32	.37	.41	.34	.53
H_2O-	08	.....	.07	.14	.....
H_2O+	.65	5.25	.83	1.02	1.38
TiO_2	.65	2.30	.92	1.19	1.80
P_2O_5	.19	.....	.05	.02	.....
CO_2	.02	.....	.....	.....	.....
S	.03	.....	.....	.....	.....
NiO	.....	.....	.16	.04	.....
MnO	.14	.18	.....	.....	.....
	100.72	100.62	100.03	100.75	100.30

1. Olivine gabbro, Sec. 23, T. 49 N., R. 15 W., West Duluth. Analyst, F. F. Grout.
2. Troctolite, Sec. 22, T. 50 N., R. 15 W., north of Proctor. A. N. Winchell, *American Geologist*, XXVI, p. 284.
3. Gabbro, Sec. 19, T. 63 N., R. 9 W. *Journal of Geology*, Vol. I, p. 712. Analyst, H. N. Stokes.
4. Gabbro, Sec. 35, T. 61 N., R. 12 W. *Journal of Geology*, Vol. I, p. 712. Analyst, H. N. Stokes.
5. Olivine gabbro, Birch Lake, *American Geologist*, XXVI, p. 181. Analyst, H. N. Stokes.

EFFECT OF THE GABBRO ON THE GREENSTONE

The Duluth gabbro forms the southern boundary of the Vermilion range from a point on the Kawishiwi River south of Twin Lakes, to Gunflint Lake. At three points along the contact the Ely greenstone is intruded by the gabbro; namely at the Kawishiwi River south of Twin Lakes, at Disappointment Mountain, and at Gabemichigama Lake. At a fourth place on the Gunflint range the gabbro and greenstone are separated by only a narrow band of iron formation (Fig. 1).

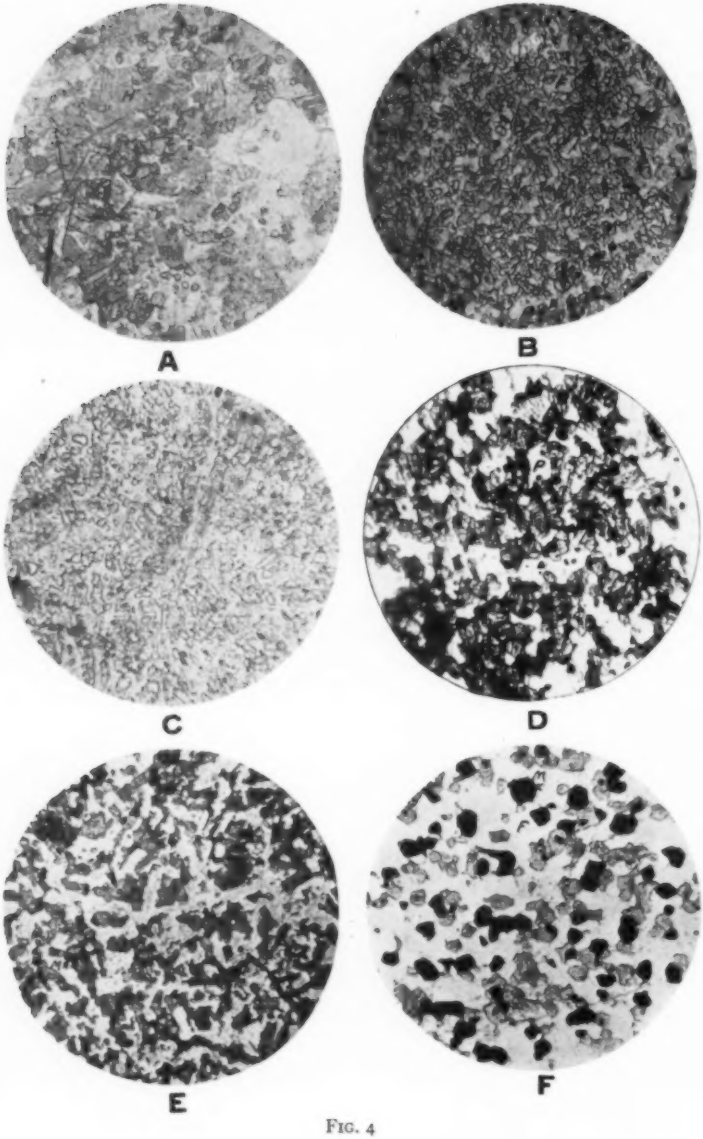

FIG. 4

EXPLANATION OF FIGURE 4

FIG. 4.—Photomicrographs of granoblasts formed at the contact of the Duluth gabbro.

A. Greenstone showing the incipient stage of alteration to a granoblast. A few rounded grains of augite (*A*) are scattered through the confused aggregate of the greenstone. Some hornblende (*H*) grains have developed. From Sec. 29, T. 65 N., R. 6 W. North of Ackley Lake. Mag. ×43.

B. Greenstone showing an intermediate stage of alteration to a granoblast. The texture is fine but globular. The rounded grains are augite and hornblende. Black grains are magnetite. Plagioclase (*P*) has not assumed euhedral forms. From near Gabemichigama Lake. Mag. ×43.

C. Greenstone with remnants of diabasic texture although altered to an intermediate stage of a granoblast. From an outcrop of ellipsoidal greenstone, 300 feet from the gabbro at Disappointment Mountain. Mag. ×43.

D. Typical granoblast probably derived from greenstone. Augite (*A*) and magnetite (*M*) are globular. Crossed nicols would show some euhedral grains of plagioclase (*P*). Note the size of the grain compared to B and C. From Muscovado Lake. Mag. ×17.

E. Granoblast from a diabase porphyry dike near the gabbro. Note that the lath-shaped feldspars (*F*) have scalloped edges. Augite (*A*) and magnetite (*M*) are the other important minerals. From the narrows at Gabemichigama Lake. Mag. ×13.

F. Granoblast from a basalt flow near the gabbro. The minerals are augite (*A*), feldspar (*F*), and magnetite (*M*). Southwest edge of Duluth. Mag. ×20.

Characteristic contact rocks occur nearly everywhere that the gabbro is in contact with the greenstone or the Huronian sediments. In the following descriptions only the contact metamorphosed greenstones will be considered. The texture of these contact rocks is especially characteristic. The rock is distinctly granular with uniform small grains two to three-tenths of a millimeter in diameter. The grains of augite and magnetite are rounded or globular in form and the feldspars have scalloped edges or are recrystallized to rounded grains showing excellent twinning bands. As a rule the rock is coarser than the normal greenstone, but finer than the gabbro. Figure 4, D, E, and F, shows the common texture of this rock. Poikilitic texture is found in a few of the contact rocks.

MINERALS OF THE GABBRO CONTACT ROCK

The minerals of the greenstone at the contact with the gabbro are, in order of abundance, plagioclase, augite, hornblende, magnetite, olivine, biotite, diallage, and hypersthene; with small amounts of chlorite, epidote, zircon, quartz, limonite, serpentine, apatite, and muscovite in some cases. Figures 8 and 11 show graphically the mineral composition of these rocks.

Plagioclase feldspar is always an important constituent. Near the contact it has entirely recrystallized and is in the form of well-twinned grains which are practically free from the alteration products so conspicuous in the normal greenstone. It varies from andesine to oligoclase.

Augite is second in abundance. Its development is traced in the description below of the gradation from normal greenstone to the contact rock. It occurs characteristically as rounded grains which are largest near the gabbro.

Hornblende is abundant only in the incipient and intermediate phases of the contact effect. Its occurrence suggests that it recrystallizes early in the contact action and then changes again to more or less globular and small grains.

Magnetite is uniformly present as small rounded grains. Olivine is rare but is found as globular shaped grains in a few cases. Other minerals are not abundant or characteristic. It is noteworthy that chlorite, calcite, quartz, leucoxene, and other alteration products

which are abundant in the normal greenstone are practically absent in the gabbro contact phase of the greenstone.

Cordierite has been described[1] as abundant in the greenstone metamorphosed by the gabbro. Apparently it is not abundant if present at all, in the specimens studied by the writer. The amount of magnesia is far too small to form 44.5 per cent cordierite in addition to other magnesian minerals, as has been suggested.

There has been a lack of a satisfactory term for gabbro contact rocks of the sort described above. They have been called muscovadite (or muscovados, muscovadytes) but this term is misleading as it suggests muscovite which is not found in the rock. The rock has also been termed a hornfels, from the hornfels texture, but in its best development the grain is much coarser than that normally referred to as hornfels, viz., cherty metamorphosed shales. Harker[2] has described a rock very similar to the contact metamorphosed greenstone and terms it a granulitic gabbro and notes that the same rock is called a pyroxene granulite by continental geologists.

Holmes[3] has recently adopted the use of the root "blast" as suggested by Becke for textural terms for metamorphic rocks. The term granoblastic is used for the texture of contact rocks of the type under discussion. This gives a satisfactory textural term but no substitute for the name muscovadite. It is suggested, therefore, that the rock be called a granoblast, because of the characteristic granoblastic texture.

GRADATION FROM NORMAL GREENSTONE TO GABBRO CONTACT ROCK

Perhaps the best idea of the profound changes in the greenstone due to the intrusion of the gabbro can be given by describing a gradation from the normal greenstone to the gabbro contact. A most excellent case is exposed at Disappointment Mountain.

A specimen 2,500 feet horizontally from the contact consists of unusually small ellipsoids, some less than an inch in diameter, and shows no apparent contact effect. In this rock kaolinized

[1] C. Zappfe, "The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-Bearing Formation," *Econ. Geol.*, Vol. VII (1912), pp. 145–78.

[2] A. Harker, *Memoirs Geol. Survey of the United Kingdom, Isle of Skye* (1904), p. 50 and Fig. 22, p. 115.

[3] A. Holmes, *Petrographic Methods*. London: Murby and Co., 1921.

plagioclase, uralitic hornblende, and magnetite are the important minerals.

At 1,600 feet from the gabbro the rock is dense and grayish green in color. It consists of about 50 per cent of much altered feldspar and much uralitic hornblende with fine magnetite in dust-like aggregates. Veins contain the unusual mineral combination of pyrite, hornblende, augite, quartz, and magnetite.

At 1,000 feet from the gabbro the greenstone shows incipient alteration due to the gabbro. It is dense, with a greenish gray color and in thin section shows a fine-grained granoblastic texture with plagioclase, augite, hornblende, and a small amount of magnetite. Both augite and hornblende occur as distinctly globular grains, whereas the feldspar is more of a matrix. The hornblende so abundant at 1,600 feet has apparently recrystallized, in part, to augite.

The rock at 600 feet is not unlike that at 1,000 feet from the gabbro, except that augite is more abundant than hornblende and the lathlike plagioclases are much scalloped or have lost their form (Fig. 4, C).

At 300 feet from the gabbro an outcrop shows good ellipsoidal structure. The texture is fine grained and globular much like the last described, but augite has almost completely replaced the hornblende. Another specimen about the same distance from the contact, but not ellipsoidal, is distinctly granular in the hand specimen. It is a typical granoblast both as to texture and minerals. A thin section shows plagioclase and augite with small amounts of magnetite, biotite, and chlorite. All of the constituents are much coarser than in the specimens farther from the contact.

The rock at 10 feet from the gabbro, and at the contact, is a granoblast much like the last described. Plagioclase and augite, with lesser magnetite and biotite, are the principal minerals.

In summary it should be noted that there is a marked change in both the textures and minerals of the greenstone near the gabbro, but the larger features, such as the ellipsoidal structure, remain essentially unchanged. Recrystallization has given the rock a granular texture and resulted in the formation of fresh plagioclase, augite, magnetite, and small amount of biotite, olivine, etc. Augite

and magnetite, especially, assume a globular form. Secondary minerals typical of the greenstone, such as uralitic hornblende, chlorite, calcite, sericite, and leucoxene, are not found in the typical contact rock. Hornblende is apparently a characteristic mineral of the incipient stages of the gabbro contact action but the fact that hornblende disappears near the contact is brought out in Figure 5.

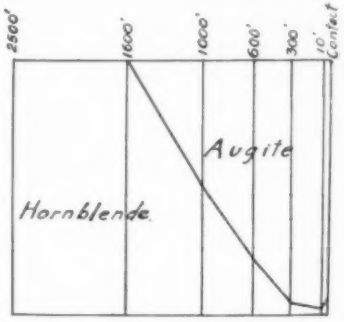

FIG. 5.—Diagram of the relative amounts of hornblende and augite in the Disappointment Mountain greenstone, from the contact to a distance of 2,500 feet.

The changes described above apply to a greenstone of the ordinary type. Some variation of the foregoing gradation occurs if the original rock is different, but there was a tendency to form rocks of the same type, regardless of original variations in minerals and textures.

CHEMICAL COMPOSITION OF THE GREENSTONE METAMORPHOSED BY GABBRO

Of the four analyses given in Table IV the first is known to be greenstone metamorphosed by the gabbro. The location and character of the others are evidence enough that they also are greenstone.

A comparison of analysis number one with the analyses of the normal greenstone and the greenstone altered by the granite, reveals no important variation except for the loss of water. Silica, iron, magnesia, and the alkalies would be the most apt to show differences. The lack of any well-defined variation in the composition of the greenstone at the gabbro contact leads to the conclusion that the gabbro has made no important contribution to the metamorphosed rock, nor in this case is it to be expected, when the small difference in composition of the gabbro and greenstone is considered. It is difficult to prove that there has been no contribution at all, because of the variability of the greenstone which makes it impossible to obtain analyses of contact and non-contact phases

which were derived from a rock known with certainty to have been originally the same.

TABLE IV

ANALYSES OF GREENSTONE GRANOBLASTS

	1	2	3	4
SiO_2	52.80	49.07	49.56	46.96
Al_2O_3	12.53	17.21	17.81	14.13
Fe_2O_3	1.01	.46	2.76	.76
FeO	7.36	12.18	9.48	14.95
MgO	9.08	3.60	5.93	15.97
CaO	11.34	9.66	9.70	2.32
Na_2O	2.69	2.96	2.87	.35
K_2O	.96	Tr.	Tr.	1.68
H_2O-	.27	.....	.50	.07
H_2O+	.21	1.55	.....	1.26
TiO_2	.78	.....	.48	.62
P_2O_5	.31	.....	.67	.03
CO_2	nd	2.70	.....	.....
ZrO_2	.04	.....	.....	.....
Cr_2O_3	.25	.....	.....	.....
MnO	.18	Tr.	.06	.93
NiO	.....	.....	.....	.06
BaO	.07	.....	.....	.....
	99.88	99.39	99.82	100.09

*1. Greenstone granoblast, 300 feet from the gabbro contact, Disappointment Mountain, SE. ¼ Sec. 26, T. 64 N., R. 8 W. Analysts, F. F. Grout, and C. W. Sanders.

2. Muscovadite (Granoblast). This rock is an inclusion in the gabbro and it is not certain that it was originally greenstone. *Final Report Minn. Geol. Survey*, Vol. V, p. 908. Analyst, A. D. Meeds.

3. Granulitic diallage gabbro (granoblast), SE. ¼ NW. ¼ Sec. 26, T. 64 N., R. 8 W. If the location is correct this is greenstone metamorphosed by the gabbro. See *U.S.G.S. Atlas* to Mon. 45, sheet XVII. W. S. Bayley, *Journal of Geology*, Vol. III (1895), p. 10. Analyst, W. H. Melville.

4. Granulitic hypersthene diallage gabbro (granoblast), SE. ¼ Sec. 20, T. 65 N., R. 4 W. If the location is correct this is also greenstone metamorphosed by the gabbro. See *U.S.G.S. Atlas* to Mon. 45, sheet XVII. W. S. Bayley, *Journal of Geology*, Vol. III (1895), p. 10. Analyst, H. N. Stokes.

* Published for the first time.

SUMMARY OF THE EFFECT OF GABBRO ON GREENSTONE

A comparison of Figures 9 and 11 and of the first and third parts of Figure 8, shows the great difference between the mineral composition of the normal greenstone and of the greenstone altered by gabbro. Feldspar is universally present in both, but has been freshened by recrystallization. Pyroxene is almost lacking in the

greenstone, but is very abundant in the contact rock. Chlorite is abundant in greenstone and practically absent at the contact. Calcite, quartz, leucoxene, sericite, and pyrite are common in the normal rock and almost lacking in the contact phase. The striking difference in texture has been described and can be seen by comparing Figures 2 and 4.

Spotted rocks, such as are typical of contact rocks in many places, were not found by the writer, although they have been observed in this region.[1]

In some of the earlier reports it was stated that there was a gradation from the gabbro to the muscovadite, as well as from the muscovadite to the greenstone. This was not true of the contacts observed by the writer and this notwithstanding the fact that the textures and minerals of the contact rock approach those of the gabbro. The distinct globular nature of the minerals in the metamorphosed greenstone and their finer grain serve to distinguish them from the gabbro in all the cases observed.

THE EFFECT OF GABBRO ON GREENSTONE PREVIOUSLY ALTERED BY GRANITE

Figure 1 shows that the Giants Range granite and the Duluth gabbro meet in Sec. 19, T. 63 N., R. 9 W., along the Kawishiwi river and both intrude the greenstone at that point. Inasmuch as the granite is older than the gabbro it is probable that the greenstone had been converted to a hornblende rock, of the type heretofore described, before the gabbro intrusion. Thus the gabbro acted on a hornblende schist rather than a normal greenstone. Specimens were collected along the north bank of the river from points opposite the gabbro at the east line of Section 19, downstream to the portage near the west line of Section 24 (Fig. 6).

The rock 1,500 feet east of the granite-gabbro contact is fairly typical of the gabbro contact. The feldspar grains are more or less broken but the edges of the grains are clear, whereas the remainder is clouded with alteration products. This undoubtedly indicates a recrystallization of the edges but the effect was not prolonged enough to change the entire crystal. Hornblende occurs as rounded

[1] C. R. Van Hise and C. K. Leith, *op. cit.*, p. 122.

grains more abundantly than augite. About 700 feet east of the contact of the granite and gabbro the greenstone is distinctly ellipsoidal, but the texture is granoblastic. Plagioclase, hornblende, augite, and magnetite are the important minerals. Small fractures cross the rock and, along the sides of these, augite is abundant, indicating a more severe action there.

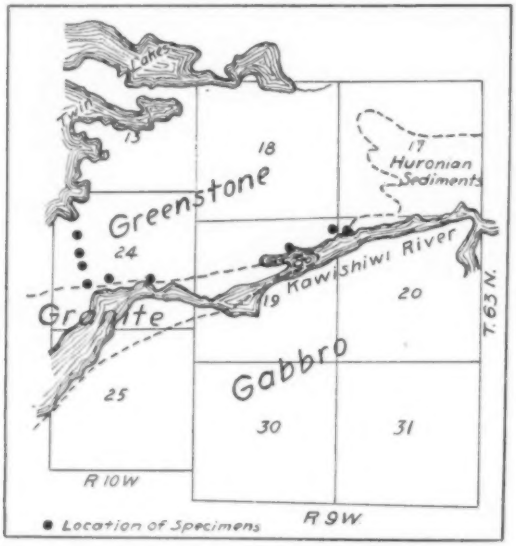

FIG. 6.—Sketch showing the location of specimens and field relations of the granite, gabbro, and greenstone on the Kawishiwi River.

A specimen of greenstone from near the granite-gabbro contact is dominantly hornblende and plagioclase with lesser biotite. The texture is granoblastic, but there are suggestions of older schistosity which has been nearly obliterated. The hornblende is in small recrystallized grains.

Farther to the west along the granite contact the ordinary hornblende schists occur.

It is apparent that a previous alteration of greenstone to a hornblende schist does not prevent the formation of a granular rock

typical of the gabbro contact. The effect is apparently not severe, as might be expected from the fact that the rock had been previously subjected to contact metamorphism of another type.

EFFECT OF THE GABBRO ON KEWEENAWAN FLOWS AND DIKES

At several places the gabbro has intruded and metamorphosed other basic rocks besides greenstone and this gives a valuable comparison.

Basic porphyry dikes were noted near Gabemichigama and Little Saganaga lakes. These show the granoblastic texture both in hand specimen and thin section. The plagioclase phenocrysts remain, but are freshened around the edge by recrystallization. The lath-shaped feldspars of the diabasic portions are scalloped in a characteristic manner (Fig. 4, E).

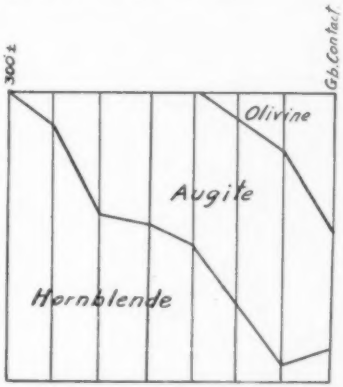

FIG. 7.—Diagram of the relative amounts of hornblende, augite, and olivine in the basalt flows near the gabbro contact at Duluth.

At the southern point of the gabbro on the southwest edge of Duluth, the gabbro is underlain by Keweenawan basalt flows. These are well exposed, especially along the railroads, and specimens are available from the contact back a distance of 300 feet. The rock farthest from the contact has a marked diabasic texture with slight hydrothermal alteration. Hornblende is abundant and is rarely euhedral but fills in around the plagioclase laths and is apparently secondary after augite. Nearer the contact, augite is present and hornblende is less abundant. The feldspars are scalloped as in the dike at Gabemichigama. The granoblastic texture is more conspicuous than the original diabasic texture. Very close to the contact olivine is abundant and there is a corresponding decrease in hornblende and augite (Fig. 7). Augite,

magnetite, and olivine have assumed the globular form and the rock as a whole shows typical granoblastic texture (Fig. 4, F).

In general it may be stated that the rocks close to the gabbro contact with either greenstone, basic porphyry dikes, or basalt flows may be so similar that it would be practically impossible to separate them on the basis of textures and minerals as seen under the microscope. Olivine is apparently more characteristic of the basalt flows near the gabbro.

The important minerals of the gabbro have been given as plagioclase, augite, olivine, and magnetite. Figure 8 shows that the same minerals, with the addition of hornblende, are characteristic of the granoblasts. Hornblende has been shown to be present abundantly only in the incipient and intermediate stages of gabbro action. Thus it may be stated with some assurance that gabbro intrusions affecting a basic rock tend to recrystallize it so that it approaches the gabbro in mineral composition, and to a certain extent in texture. This is true whether the basic rock is relatively fresh as are the Keweenawan flows and dikes, or much katamorphosed as is the Ely greenstone.

COMPARISON WITH OTHER DISTRICTS

It should be noted that some such effects have been described for gabbro contacts in other regions, although no other case is known where the phenomena are so clearly shown as along the Duluth gabbro.

As early as 1874 Judd (2)[1] described the field relations where gabbro and dolerite intrude basalts in Scotland. Unfortunately the mineral changes were not described.

Geikie (4) in a discussion of the Tertiary volcanic action of the British Isles describes the contact effect of gabbro and granophyre on basalts. The basalts include varied types often diabasic; Geikie's summary of Hatch's note on the thin sections shows that the minerals tend to assume granular forms, rounded granules being especially noteworthy. Augite, magnetite, and plagioclase are the abundant minerals.

Brogger (12) has noted the formation of hypersthene along the contact of an olivine diabase in the Ogygie shales. The same shales in contact with a syenite showed no hypersthene.

[1] Numbers in parentheses refer to the Bibliography.

Harker (13, 17) has described the effect of the gabbro of Carrock Fell on basalts. The feldspars have lost their inclusions, hornblende develops from the chlorite and serpentine, and fresh augite is present in some cases.

Geikie (18) noted the altered basalts intruded by dolerite plugs. The microscope shows the altered basalt to be a confused aggregate of colorless microlites (feldspar?) and innumerable grains of magnetite.

Harker (27) described the intrusion of the gabbro on the Isle of Skye as developing a "granulitic" structure at places in the basalt. Harker gives a photomicrograph of this granulitic rock that is strikingly like the greenstone altered by the gabbro in Minnesota. The Skye rock consists essentially of an aggregate of labradorite and augite with little octahedra of magnetite.

Goldschmidt (33) described the development of a hornfels zone around a basic essexite. This zone he states is not developed around granite and syenite contacts. Photomicrographs of the hornfels show that they develop granoblastic textures.

From the foregoing summaries it is apparent that basic rocks such as basalts when affected by basic intrusives tend to recrystallize to a granular or globular aggregate. Plagioclase, augite, hypersthene, and magnetite are the minerals most frequently noted. In general the scant evidence obtainable in the literature confirms the conclusions drawn from a study of the contact effect of the Duluth gabbro.

VI. COMPARISON OF GRANITE AND GABBRO EFFECTS

MINERAL COMPOSITION

The mineral composition of the thin sections of forty-nine normal greenstones, thirty-seven greenstones metamorphosed by granite, and thirty-one metamorphosed by the gabbro are shown graphically in Figures 8 to 11.

The normal greenstone, the rock from which the hornblende schists and granoblasts were formed, is composed mainly of feldspar, chlorite, hornblende, epidote, and magnetite, with minor amounts of other minerals especially secondary calcite, quartz, leucoxene, sericite, and so on. Chlorite is the characteristic mineral.

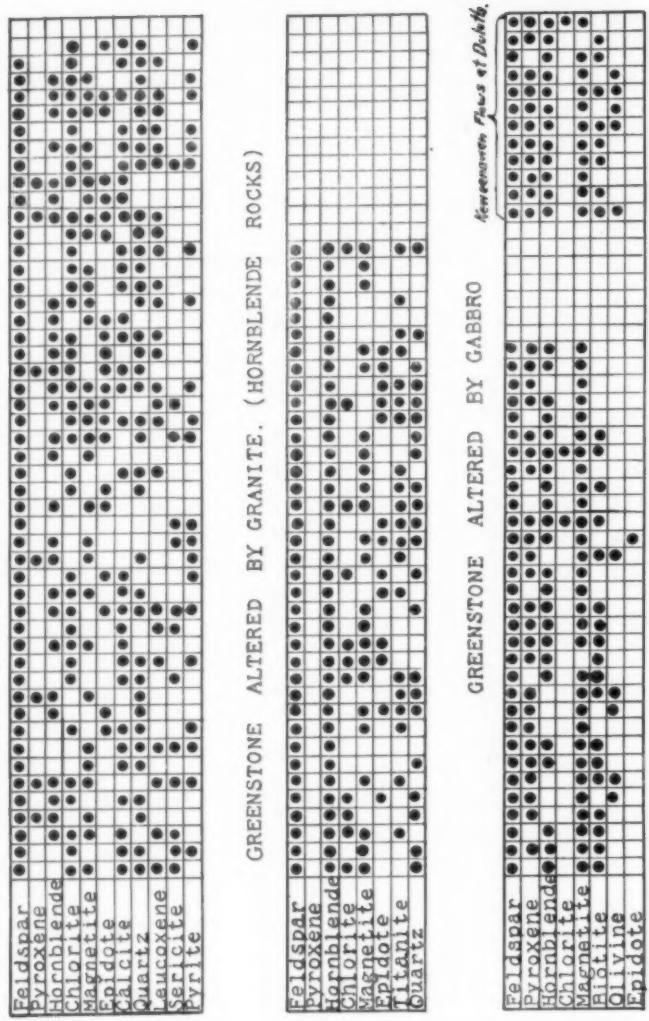

FIG. 8.—Diagram showing in vertical columns the important minerals present in each thin section of the three phases of the greenstone.

The greenstone that has been metamorphosed by the granite is normally a hornblende schist in which the principal minerals are hornblende, feldspar, and magnetite, with only minor amounts of other minerals of which titanite and quartz are apparently the most important. Hornblende is the characteristic mineral.

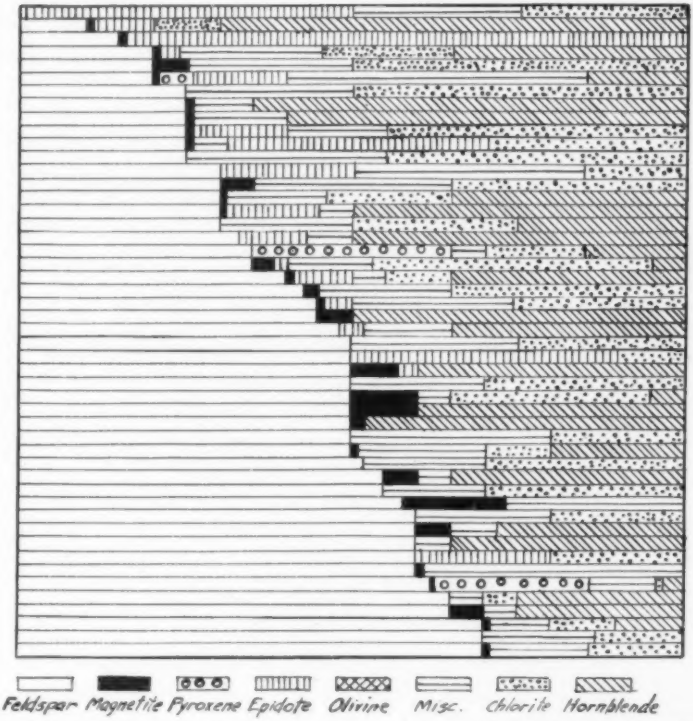

FIG. 9.—Diagram of the estimated modes of the normal greenstones. Note the abundance of chlorite.

The greenstone near the gabbro contact is composed mainly of feldspar, augite, hornblende, and magnetite, with minor amounts of other minerals, of which only biotite and olivine are of much importance. Hornblende is not found in large amounts close to the contact. Augite is the characteristic mineral.

Thus it is possible to state very simply the contrast in mineral composition at the two contacts. Feldspar is freshened by the gabbro and not by the granite. Hornblende is the abundant ferromagnesian mineral at the granite contact, whereas augite is abundant at the gabbro contact. Magnetite is present in both contact rocks, but is apparently more abundant near the gabbro and less abundant near the granite than in the normal greenstone.

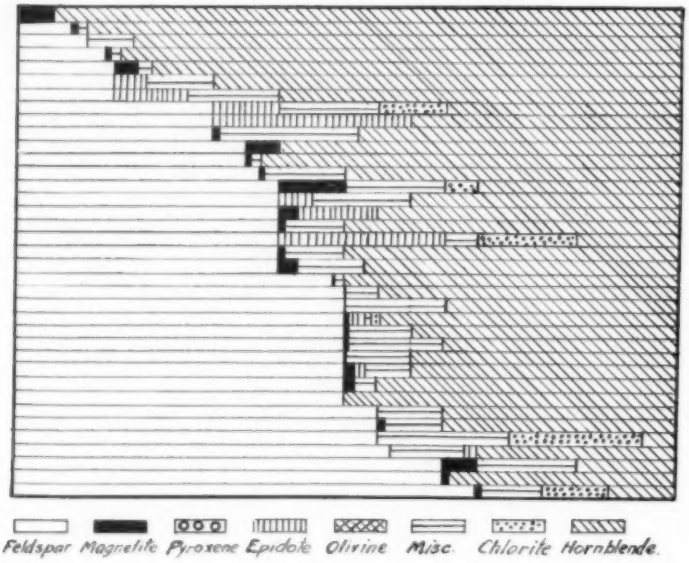

FIG. 10.—Diagram of the estimated modes of the greenstone altered by the granite. Note the abundance of hornblende.

Apparently iron oxide is eliminated in recrystallization of the ferromagnesian minerals by the gabbro and absorbed in the formation of hornblende by the effect of the granite. The reverse is apparently true of quartz as it is a common constituent near the granite but practically absent near the gabbro. Titanite, although only a minor constituent, is present in more than half of the hornblende schists, but is practically lacking in the granoblasts.

Inclusions in the granite indicate that the greenstone may be almost entirely recrystallized to hornblende, but no tendency to form a single mineral was noted near the gabbro.

STRUCTURES AND TEXTURES

In general the larger original structures of the greenstone are retained in the contact phases, so there is little contrast between the granite and gabbro zones except that schistosity is often superimposed on the other structures near the granite. The original

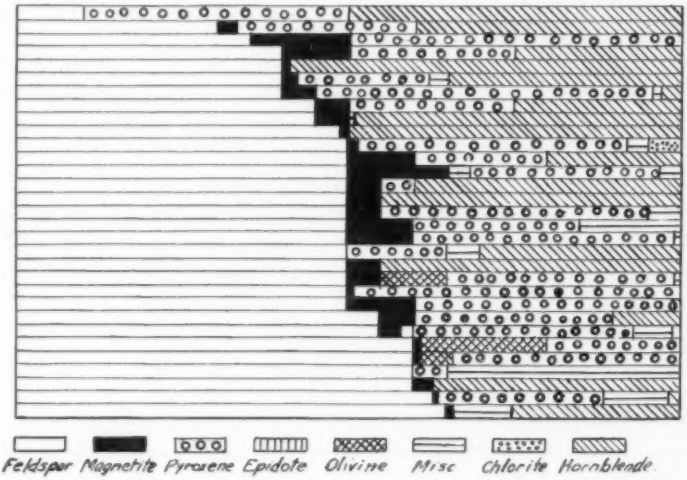

FIG. 11.—Diagram of the estimated modes of the greenstone altered by the gabbro (granoblasts). Note the abundance of pyroxene.

greenstone is, as a rule, a confused aggregate in many cases showing remnants of diabasic texture. Schistosity is characteristic of the granite contact, whereas granoblastic texture in which the grains are uniform and rounded, is universal near the gabbro. A comparison of Figures 2 and 4, shows the difference in texture of the three phases. Feldspar is an important mineral in both phases, but its texture is entirely different in the two rocks. In the hornblende schist it is normally broken up to form a mosaic and the individual fragments are usually clouded with sericite, etc., and twinning

bands are rarely shown. In the well-developed granoblasts the feldspar has entirely recrystallized to uniform small grains which are free from alteration products and show twinning rivaling that of a fresh igneous rock.

CHEMICAL COMPOSITION

The tables of analyses of the three phases of the greenstone and of the granites and gabbros show considerable variation in each of the three types of rock, but a detailed comparison indicates that there is no constituent except H_2O which is consistently different in any one of the types as contrasted with the other two. This is rather unexpected inasmuch as the mineral composition of the three phases have been shown to be different and the results given in most studies of contact metamorphism indicate that alkalies especially are added to rocks metamorphosed by granites. The H_2O content of both contact rocks is distinctly below that of the normal greenstone. A specific example will, perhaps, best emphasize the lack of close relation between mineral and chemical composition. Figures 9, 10, and 11 show that magnetite is a constituent of most specimens of each phase. It is more abundant in the gabbro contact rock, and less abundant at the granite contact, than in the normal greenstone. Nevertheless the amount of total iron oxides shown in the analyses is about the same for the three phases. It is worthy of mention that the average Fe_2O_3 of the gabbro phase is lower than that of the other two, whereas the FeO is considerably higher.

It may be concluded that as far as available analyses show there is little difference in the composition of the greenstone metamorphosed by granite or gabbro and that contributions from the intruding rocks have not played an important part in contact metamorphism in this case. It should be noted in this connection that there is a significant absence of minerals such as tourmaline, garnet, etc., which are commonly found at contacts where contributions have been important. Tourmaline was not identified in any of the seventy specimens of the contact phases of the greenstone. Garnet was found in one specimen of hornblendite from White Iron Lake. With the exception of the rare occurrence of pyrrhotite

no other minerals suggestive of contributions were noted by the writer.

In the earlier reports by Winchell, Clements, and others noted above, minerals suggestive of contribution are rarely mentioned. Clements[1] suggested the possible addition of material because of the increased amount of magnetite and hornblende. Broderick[2] has shown that titanium is added to the metamorphosed iron formation included in the gabbro. The low titanium content of the greenstone granoblasts indicates that this was unimportant along the greenstone contact. Nebel[3] reported tourmaline in greenstone metamorphosed by the gabbro, but it was evidently local.

CAUSES OF THE DIFFERENCE IN GRANITE AND GABBRO CONTACT EFFECTS

A notable difference in the contact metamorphic effect of granite and gabbro on the Ely greenstone has been described in this paper. Chemical analyses of the rocks involved show no conclusive evidence of direct contribution from the intrusives as the cause of this difference, and it is therefore necessary to consider the possible physical effects. The importance of the physical effects has recently been discussed by Johnston and Niggli.[4]

TEMPERATURE

It has been recognized by many workers that the temperature of magmas varies to a considerable extent, and that, in general, acid magmas remain molten at much lower temperatures than basic magmas,[5] and thus there seems to be a good foundation for

[1] J. M. Clements, *op. cit.*, p. 162.

[2] T. M. Broderick, "The Relation of the Titaniferous Magnetites of Northeastern Minnesota to the Duluth Gabbro," *Econ. Geol.*, Vol. XII (1917), pp. 663–98.

[3] N. L. Nebel, *Econ. Geol.*, Vol. XIV (1919), p. 393.

[4] J. Johnston and P. Niggli, "The General Principles Underlying Metamorphic Processes," *Journal of Geology*, Vol. XXVI (1913), pp. 481–516.

[5] A. Harker, *Natural History of Igneous Rocks* (1909), p. 186; J. P. Iddings, *The Problem of Vulcanism* (1914), p. 108; Lehmann, *Alltkrystallischen Schiefergesteine* (1884), pp. 54–55; J. Barrell, "Relations of Subjacent Igneous Invasions to Regional Metamorphism," *American Journal of Science*, Vol. I (1921), p. 174; Wright and Larsen, "Quartz as a Geologic Thermometer," *American Journal of Science*, Vol. XXI (1905), p. 447; R. A. Daly, *Igneous Rocks and Their Origin* (1914), p. 274; N. L. Bowen, "The Behavior of Inclusions in Igneous Magmas," *Journal of Geology*, Vol. XXX (1922), pp. 520–23.

the belief that basic magmas are intruded at a considerably higher temperature than granitic magmas.

Furthermore, since rocks are poor conductors of heat, the actual temperature of intrusions is not necessarily an index of the temperature to which the invaded rock is heated.[1] However, as noted by Lindgren,[2] Harker,[3] Barrell,[4] and others, the heating of the intruded rock is not dependent on conduction of heat, but to a greater extent on the heat carried by the gases given off by the magma which permeate the intruded rock for some distance. A more severe effect along veins and fissures has been noted in the greenstone near both the gabbro and granite, which would indicate such a condition. The gases given off by the gabbro might be expected to be hotter than those of the granite and thus would raise the temperature of the intruded rock to a greater degree. Little data are available on the point, but it seems logical to assume that such a difference in temperature would be responsible for the difference in texture and mineral composition of the rock at the two contacts. Carbon steels show a wide variation in texture depending on heat treatment. When reheated above a certain temperature and allowed to cool slowly granular textures not unlike that of the granoblasts are developed.

Harker[5] says, "we may confidently assume from experimental evidence that augite crystallizes at high temperatures, enstatite probably not so high, and hornblende at low temperatures." In general this explanation would agree with Grubenmann's[6] zones of metamorphism and the minerals assigned to these zones. His middle zone is characterized by high temperature, intense stress, etc., and hornblende is assigned to this zone. The lowest zone is characterized by high temperatures, etc., and augite is

[1] Zobel and Ingersoll, *An Introduction to the Mathematical Theory of Heat Conduction with Engineering and Geological Applications.* Ginn & Co., 1913.

[2] W. Lindgren, "The Origin of Garnet Zones and Associated Ore Deposits" (a discussion), *Econ. Geol.*, Vol. XIX (1914), pp. 283–92.

[3] A. Harker, *Natural History of Igneous Rocks* (1909), p. 189.

[4] J. Barrell, "Geology of Marysville Mining District," *U.S. Geol. Survey Prof. Paper 57* (1907), pp. 116–50.

[5] A. Harker, *op. cit.*, p. 187.

[6] Grubenmann, *Die Krystallinen Schiefer*, Vol. I, 1904; Vol. II, 1907.

among the minerals developed. Thus it may be concluded that there is reason to believe that one cause of the development of hornblende by the granite and augite by the gabbro is the difference in temperature to which the greenstone was heated.

PRESSURE

Considering the texture of the rock at the granite contact which is normally schistose, whereas that at the gabbro is granular, it would seem that pressure and especially differential stress might be a cause of the difference in the contact effect. However, hornblende, the important mineral of the schist, is also developed in the incipient stages of the gabbro effect, but in this case schistosity is not developed. This seems to indicate that stress was not the cause of the formation of hornblende but was only instrumental in orienting it.

In the roof of a batholith more or less differential stress and movement are probably effective. There is even the possibility of the intrusion of the granite being correlated with the folding in the region as is indicated by the linear extent of the Giant's Range granite and its general correspondence in trend with the folds which were developed at about the time of intrusion. Thus it is probable that the texture of the rock at the granite contact was developed under conditions of differential stress which caused the orientation of hornblende generated by other causes, while in the case of the gabbro static conditions prevailed.

WATER

The abundance of water vapor and other mineralizers and gases in acid magmas has been shown in many ways; likewise the relative dryness of basic magmas. The rocks developed along the granite contacts are characterized by hornblende and those along the gabbro by augite. It remains to be seen if there is any possible connection between these facts.

Water has been shown by Penfield and Stanley[1] to enter in the formation of the amphiboles. They state "that fluorine and hydroxyl are integral parts of the amphibole molecule and that they

[1] S. L. Penfield and F. C. Stanley, "On the Chemical Composition of Amphibole," *American Journal of Science*, Vol. XXIII (1907), pp. 23–51.

are to be regarded as isomorphous with the protoxides is considered as definitely proven by the results of the analyses." Analyses of the pyroxenes show a very small water content, and there is a lack of data to show that this small amount is a part of the molecule. Thus it is possible that the formation of the two minerals is due to the relative amounts of water in the granite and gabbro magmas. There is, of course, no necessity of a contribution of water from the magma, as is clearly shown by the water content of the normal greenstone. It is rather a question of relative dehydration. That the granite did not cause complete dehydration of the greenstone is indicated not only by the hornblende in the contact rock, but by the presence of sericite and other hydrous minerals even in direct contact with the granite. On the contrary the gabbro effect is a thorough dehydration. Kaolin, sericite, chlorite, and other hydrous minerals disappear in the early stages and the feldspar near the contact is recrystallized to exceptionally clear grains which are in marked contrast to the cloudy feldspar near the granite. It must be admitted that available analyses of the contact rocks show about the same water content for both phases, but in either case it is small and the amount has undoubtedly been affected somewhat by exposure to weathering since the specimens are from the surface of outcrops.

In general it may be concluded that there is a basis for the belief that the lower temperature and higher water content of the granite magmas is responsible for the formation of hornblende in the greenstone near the granite, and the higher temperature and relative dryness of the gabbro magma favored dehydration and recrystallization resulting in augite.

VII. SUMMARY

This paper is a study of the contact metamorphism of a basic rock by both basic and acid intrusives. The Ely greenstone was selected because it is the most widespread available basic rock, but other cases have been noted. The principal points brought out are as follows:

1. The Ely greenstone of the Vermilion range originally consisted of basalts showing ellipsoidal, amygdaloidal, spherulitic, and tuffaceous structures and, for the most part, a diabasic texture.

2. The normal greenstone is much altered and the original minerals with the exception of feldspar have practically disappeared. The important minerals are: feldspar, uralitic hornblende, chlorite, magnetite, epidote, quartz, calcite, sericite, and pyrite. The rock is as a rule somewhat schistose.

3. Calcite is notably abundant. Due to its rather constant association with sericite, it was concluded that the calcite was a result of hydrothermal alteration.

4. Chemical analyses of the greenstone show that though variable it is always low in silica.

5. Four masses of granite intrude the Ely greenstone on the Vermilion range. Three are hornblende granites and one a biotite granite.

6. Wherever granites intrude it, the greenstone is metamorphosed to a hornblende rock which is normally a schist. A gradation may be traced from normal greenstone to the entirely recrystallized rock at the contact.

7. Notwithstanding the schistosity of the granite contact rock the larger features such as the ellipsoidal structure, are not as a rule destroyed.

8. The important minerals of the greenstone at the granite contacts are feldspar, hornblende, magnetite, quartz, and titanite. There is a tendency near the contact for all minerals except hornblende to disappear, and directly at the contact or in inclusions, hornblende may constitute practically the entire rock.

9. Inclusions of greenstone in the granites are changed to hornblendites and in the biotite granite hornblende may be converted to biotite, probably by reaction rather than by fusion.

10. Chemical analyses of the hornblende schists formed at the granite contacts show no conclusive evidence of contribution from the granite.

11. A survey of the literature shows that hornblende rocks are characteristic of the contacts where acid rocks are intruded into basic rocks.

12. The Duluth gabbro intrudes and metamorphoses the Ely greenstone and the contact is exposed in four areas on the Vermilion range. A gradation may be traced from normal greenstone to entirely recrystallized contact rocks.

13. The larger structures of the greenstone are preserved near the contact, but the texture is entirely changed to an aggregate of rounded grains for which the term granoblastic texture is used.

14. The important minerals of the gabbro contact rock are augite, recrystallized plagioclase, and magnetite, with lesser biotite, hypersthene, olivine, etc. Hornblende is an intermediate mineral which disappears near the contact. The minerals are similar to those of the original greenstone and to those of the gabbro.

15. Chemical analyses of the greenstone at the gabbro contact fail to show evidence of contribution from the gabbro.

16. Where the gabbro has intruded the fresh Keweenawan basic flows and dikes, the metamorphism has resulted in a granular rock, essentially like that of the metamorphosed greenstone.

17. Descriptions of the metamorphism of basic rocks by basic intrusives in other districts show changes similar to those described in the Ely greenstone.

18. Since it has been shown that the temperature of basic igneous magmas is higher than that of acid magmas, it is suggested that this is in part a cause of the difference in the contact metamorphic effect of the two types; for example, the formation by the granite of a rock high in hornblende, and one by the gabbro high in augite.

19. There is evidence that acid magmas in general have a considerable content of water whereas basic magmas are relatively dry. This is suggested as a further possible cause of the difference in metamorphism, as the minerals formed at the gabbro contact indicate a relatively greater dehydration than those formed near the granite.

BIBLIOGRAPHY ON THE CONTACT METAMORPHISM OF BASIC IGNEOUS ROCKS OF OTHER DISTRICTS

1. Sir A. Geikie, "On the Tertiary Volcanic Rocks of the British Isles, *Q.J.G.S.*, Vol. XXVII (1871), pp. 279–311.
2. J. W. Judd, "On the Secondary Rocks of Scotland," *Q.J.G.S.*, Vol. XXX (1874), pp. 220–301.
3. S. Allport, "On the Metamorphic Rocks Surrounding the Land's End Mass of Granite," *Q.J.G.S.*, Vol. XXXII (1876), pp. 407–27.
4. Sir A. Geikie, "History of the Volcanic Action during the Tertiary Period in the British Isles," *Trans. Roy. Soc. Edinburgh*, Vol. XXXV (1885), pp. 21–184.

5. J. J. H. Teall, *British Petrography*. London, 1888.
6. J. W. Judd, "On the Propylites of the Western Isles of Scotland," *Q.J.G.S.*, Vol. XLVI (1890), pp. 341–85.
7. H. Beck, "Über die Amphibolitizerung von Diabasgesteinen im Contactbereich von Graniten," *Zeitsch. Deut. Geol. Gesellschaft*, Vol. XLIII (1891), pp. 257–63.
8. A. Harker and J. E. Marr, "The Shap Granite and the Associated Igneous and Metamorphic Rocks," *Q.J.G.S.*, Vol. XLVII (1891), pp. 266–327.
9. R. Beck, "Die Contacthöfe der Granite und Syenite, etc.," *Mineral. und Petrogr. Mittheilungen*, Vol. XIII (1892), pp. 290–342.
10. J. W. Judd, "On Inclusions of Tertiary Granite in the Gabbro of Cullinan Hills," *Q.J.G.S.*, Vol. XLIX (1893), pp. 175–95.
11. A. Harker and J. E. Marr, "Metamorphic Rocks around the Shap Granite," *Q.J.G.S.*, Vol. XLIX (1893), pp. 359–70.
12. W. C. Brögger, "The Basic Eruptive Rocks of Gran," *Q.J.G.S.*, Vol. L (1894), pp. 15–38.
13. A. Harker, "On the Gabbro of Carrock Fell," *Q.J.G.S.*, Vol. L (1894), pp. 311–37.
14. J. G. Goodchild, "Augen-Structure in Relation to the Origin of Eruptive Rocks and Gneiss," *Geol. Mag.*, Vol. XXXI (1894), pp. 20–27.
15. W. J. Sollas, "On the Volcanic District of Carlingford and Slieve Gullion," *Trans. Roy. Irish Acad.*, Vol. XXX (1894), pp. 477–512.
16. Zirkel, *Lehrbuch der Petrographie*, Vol. II. Leipzig, 1894.
17. A. Harker, "Carrock Fell, a Study in the Variation of Igneous Rock Masses," *Q.J.G.S.*, Vol. LI (1895), pp. 125–48.
18. Sir A. Geikie, "The Tertiary Basalt Plateaux of Northwestern Europe," *Q.J.G.S.*, Vol. LII (1896), pp. 331–406.
19. A. Harker, "On Certain Granophyres, Modified by the Incorporation of Gabbro Fragments in Strath, Skye," *Q.J.G.S.*, Vol. LII (1896), pp. 320–30.
20. Sir A. Geikie, *Ancient Volcanoes of Great Britain*, Vol. II. London, 1897.
21. J. Parkinson, "On an Intrusion of Granite and Diabase at Sorel Point, Northern Jersey," *Q.J.G.S.*, Vol. LV (1899), pp. 430–48.
22. K. Busz, "On a Granophyre Dyke Intrusive in the Gabbro of Ardnamurchan, Scotland," *Geol. Mag.*, Vol. XXXVII (1900), pp. 436–41.
23. J. Barrell, "Microscopical Petrography of the Elkhorn Mining District," *Twenty-second Annual Report U.S. Geol. Survey* (1901), pp. 505–49.
24. H. Kynaston, "Notes on Contact Metamorphism Round the Cheviot Granite," *Trans. Edin. Geol. Soc.*, Vol. VIII (1901), pp. 18–26.
25. G. O. Smith and F. C. Calkins, "The Cascade Range near the 49th Parallel," *U.S. Geol. Survey Bull. 235* (1904).
26. D. H. Erdmannsdörfer, "Die Devonischen Eruptivgesteine und Tuffe bei Harburg und ihre Umwandlung im Kontakthof der Brockenmassive," *Jahrb. K. Pr. Geol. Landensanstalt für 1904*, Vol. XXV.
27. A. Harker, "The Tertiary Igneous Rocks of Skye," *Memoir Geol. Survey of the United Kingdom* (1904).

28. Sir A. Geikie, *Structural and Field Geology* (1905).
29. H. Rosenbusch, *Mikroschpische Physiographie die Mineralien und Gestein*, Vol. II, 1907.
30. C. Reid and J. S. Flett, "The Geology of the Land's End District," *Memoir Geol. Survey of England and Wales* (1907).
31. F. E. Wright, "The Intrusive Rocks of Mount Bohemia," *Michigan Geol. Survey Annual Report for 1908*, pp. 361–93.
32. A. Harker, *Natural History of Igneous Rocks*. New York, 1909.
33. Goldschmidt, *Die Kontaktmetamorphise im Kristianiagebiet, Skrifter utgit av Videnskatsselskafet*. Kristiania, 1912.
34. W. H. Collins, "The Gowganda Mining District," *Canada Department of Mines, Geol. Survey Memoir 33* (1913).
35. Weigel, "Über einige Erzlagerstätten," *Neues Jahrb. für Min.*, Vol. XXXVII (1914), pp. 653–739.
36. L. V. Pirsson, "Microscopical Characters of Volcanic Tuffs," *American Journal of Science*, Vol. XL, 4th ser. (1915), pp. 191–211.
37. F. Rinne, *Gesteinskunde*, p. 187. Leipzig, 1921.

THE DALLES TYPE OF RIVER CHANNEL

J HARLEN BRETZ
University of Chicago

ABSTRACT

Streams of large volume with high gradient, flowing over closely and vertically jointed rock, pluck rather than abrade. They erode rock basins in mid-channel without waterfalls or eddies. The channels are multiple and anastomose very irregularly. Flat-topped, vertically-walled rock islands are left among the channels. The type is the Dalles of Columbia River. Homology between the present Dalles channels and great areas of "scabland" on the Columbia Plateau north of Snake River is indicated. The "scablands" are the channels of enormous Pleistocene rivers across the plateau.

Columbia River flows on the Columbia basalt formation from Rock Island Rapids, near Wenatchee, Washington, to Cooks, Washington, a total distance of 300 miles. Rapids are numerous along this course in low water, at least 40 of them of sufficient prominence to bear names. The greatest of all are the several rapids between Fallbridge, Washington, and The Dalles, Oregon, commonly grouped together as "The Dalles of the Columbia." The river for 125 miles upstream and a few miles downstream flows in the bottom of a broad syncline and the group of rapids is located on a minor upwarp of this floor.

A contour map of the group is shown in Figure 1. The entire length is 12 miles and the total low-water fall of the river surface is 81 feet, of which 20 feet occurs in a sheer drop at Celilo Falls. Ten Mile Rapids is half a mile long. At low water it is a straight chute, 150 to 300 feet wide. Five Mile Rapids (the original "Dalles") is a mile and a half long and similarly at low water is a nearly straight chute 150 to 300 feet wide. Due to an especially favorable setting for a dam and power plant, this rapid has been surveyed carefully and a part of it has been sounded. Three Mile Rapids is a little more than a quarter of a mile long and at low water is a narrow, crooked channel. At extreme high water almost the whole area shown in Figure 1 is overflowed. Celilo Falls then

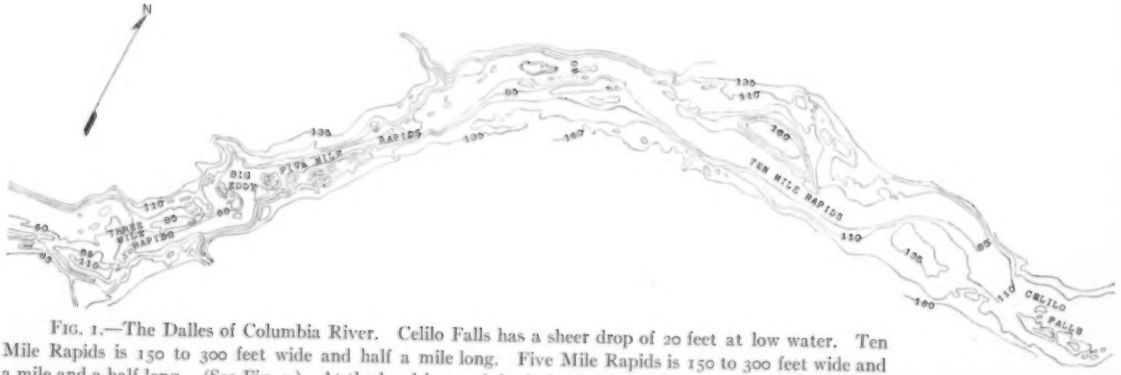

FIG. 1.—The Dalles of Columbia River. Celilo Falls has a sheer drop of 20 feet at low water. Ten Mile Rapids is 150 to 300 feet wide and half a mile long. Five Mile Rapids is 150 to 300 feet wide and a mile and a half long. (See Fig. 2.) At the head is a rock basin in the river bottom 90 feet deep shown in detail in Fig. 4. Big Eddy is 150 to 200 feet deep. Three Mile Rapids is 1,500 feet long. Total length from Celilo Falls to foot of Three Mile Rapids is 12 miles Total fall at high water is 60 feet, at low water 81 feet. At extreme high water almost the entire area here shown is submerged. Redrawn from a map accompanying report, Chief of Engineers, U.S. Army, 1912. Contours renumbered, with mean sea-level as datum.

becomes a rapid; indeed, the entire stretch is one long rapid with a total descent in the surface of the river of about 60 feet.

At the head of Five Mile Rapids the extreme recorded range between high and low water is 93 feet. At the foot, it is 71 feet. At times of notable flood, the river covers most of the area shown in Figure 2 between the navigation canal on the Oregon side and the Spokane, Portland and Seattle Railroad on the Washington side. The gradient of the river surface then is 20 feet to the mile and the flow may exceed one million second-feet.[1] The contoured surfaces shown in Figures 1 and 2 are therefore essentially the bottom of a very large, high-gradient river channel, mapped at low-water stage. From Figure 1 it is clear that the character of the channel floor is the same throughout the entire 12 miles. There is a multitude of flat-topped knobs and small hills of basalt, with precipitous sides descending to the numerous channels which ramify among the knobs. See Figures 4 and 5. Though closely associated, the summits of the knobs and the floors of the channels are at various altitudes. The channels are also of varying depths, widths, and ground plans, and there are many rock basins in them. In Figure 2 these characters are seen to extend to much smaller dimensions than shown in Figure 1 and the precipitous cliffs stand out more clearly. At high water practically all the eminences are submerged, at low water most of the channels go dry. At intermediate stages the pattern of rock islands and channels, and the location of areas of broken water vary greatly.

Figure 6[2] shows the subaqueous topography of a small portion of Five Mile Rapids. The river here at low water is only 150 feet wide at the narrowest place. Tremendous scour of the channel floor is to be expected, yet one is surprised to find that the soundings show a hole in the bottom of the river 170 feet below low-water level, 115 feet below sea-level[3] and at least 90 feet below the channel

[1] A flood of 800,000 second-feet occurs about once in five years. The maximum flood recorded was in 1894 when 1,170,000 second-feet passed The Dalles, Oregon. Only two North American rivers, the Mississippi and the Ohio, have ever had greater measured floods.

[2] I am indebted to Mr. L. F. Harza's report entitled *Columbia River Power Project near The Dalles, Oregon* (Technical Publishing Co., San Francisco, California, 1914), for Figures 2 and 6 and for most of the numerical data used in this paper.

[3] It is 192 miles by river from this place to the ocean.

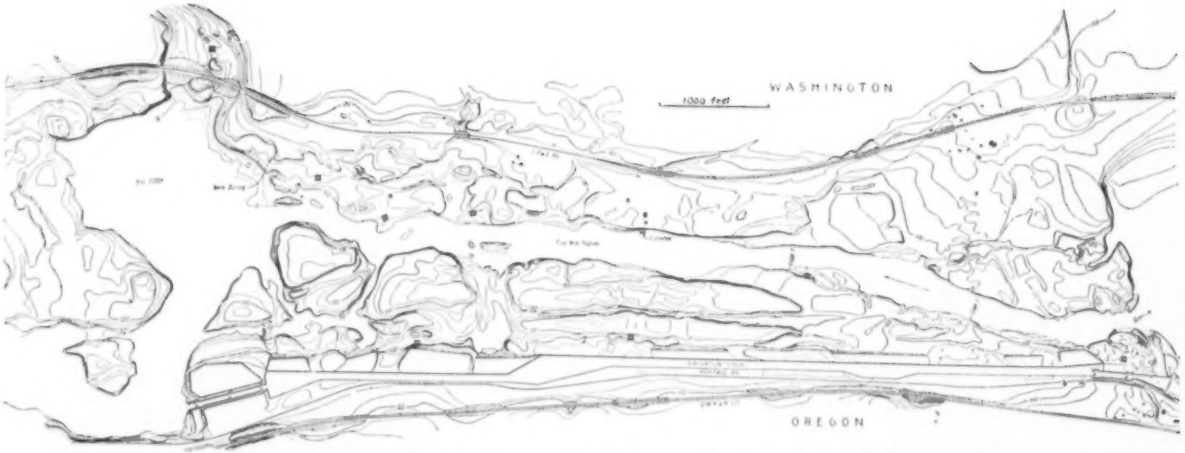

FIG. 2.—Five Mile Rapids and Big Eddy, contoured to low-water level. Contour interval 10 feet. Hachures along the railroads and canal indicate grades and spoil heaps. (After L. F. Harza, *Columbia River Project near The Dalles, Oregon*, Fig. 9.)

floor immediately downstream. The highest altitude of the river bottom between the head of Five Mile Rapids and the ocean is not known. It probably is at least 20 feet above sea-level. The hole in such case is a closed depression 135 feet deep.

And the topographic expression of the bottom of this hole is essentially the same as that of the high water channel floor. There are knobs here 40 to 60 feet high, though their summits are hardly above sea-level, and there are channels with precipitous sides among these knobs.

Big Eddy, immediately below Five Mile Rapids, has not been sounded in detail but its maximum known depth is 150 feet below low-water level. It may be much deeper. No other channel soundings in the 12 miles of rapids are known to the writer. A fair inference is that many submerged knobs, channels, and holes exist.

The basalt exposed in the high-water channels is but little smoothed by abrasion. Though it is disrupted by frost action, the existence of some smoothed surfaces shows that abrasion during high water more than keeps pace with disintegration by frost during the winter low water. The rough, hackly surface of the channel floor is due largely to fracturing and plucking of the closely jointed basalt during floods. So far as abrasion is a major factor, it is from the blows struck by large fragments in transit and results in fracturing rather than wearing. The flattish summits of the inter-channel eminences and the precipitous sides of the channels are equally good evidence of plucking of the horizontally-bedded, vertically-columned lava. And the great hole at the head of Five Mile Rapids, not a pothole either by eddy or by cataract mechanics, is due to the plucking of the jointed basalt by the tremendous currents engendered in the local constriction. The débris from the bottom of the hole is hoisted by these currents at least 90 feet to clear the down-stream rim. Yet the rim remains! Abrasion is a minor item. Plucking is the major item.

Eddies, however, are of great importance in the production of the Dalles type of river channel. Given the incision of a somewhat irregular initial course across a basalt surface, every deflection against the channel wall constitutes a maximum exposure to pluck-

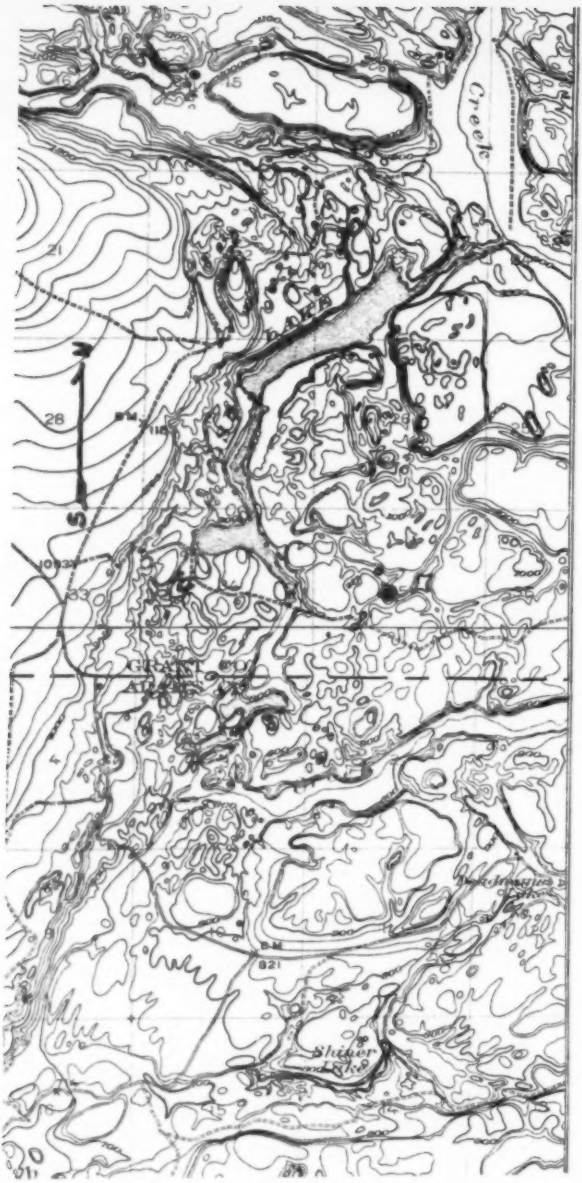

FIG. 3.—Abandoned Dalles-type river channels, a few miles south of Moses Lake, Washington. Part of Corfu Quadrangle. Contour interval 25 feet. The area shown is a part of the Pleistocene Drumheller Channels. The gradient of the deepest channel is about 25 feet to the mile. The flat-topped island-like knobs and hills of varying altitudes bear the same relations to the ramifying channels of varying depths and altitudes of floors as at Five Mile Rapids. The bottom of one rock basin (desiccated) is 75 feet below its downstream rim. Depth of Goose Lake is unknown. It is dammed by a rock rim. Compare its great eddy pocket with Big Eddy at the foot of Five Mile Rapids.

ing. The loss of columns means enlargement of the channel here until a pocket and an eddy or whirlpool off the original main course results. Besides Big Eddy, which is of this genesis, the sites of several such at high water can be located on Figure 2.

Rock Island Rapids, near Wenatchee, Washington, is another Dalles type of river channel with flat-topped and steep-walled islands of basalt interrupting and widening the river despite a much steeper gradient here than above or below. So are the cascades of Spokane River, commonly known as Spokane Falls, in the city of Spokane. There are but few falls here; most of the descent

FIG. 4.—South side of Five Mile Rapids, near west end. Photograph taken at an intermediate river stage, looking diagonally downstream.

is by steep chutes which divide and unite and bend about the basalt islands and in some places make noteworthy eddies in great alcoves off the main channel. Island-like hills of basalt, now above the reach of flood waters, exist in the built-up blocks of the city on both sides of the river. They belong to the series and record the earlier stages when the river was experimenting with a number of channels and had not yet selected its future main course. A tract along Yakima River between Mabton and Byron is another example of the Dalles type of river channel, though it has now been entirely abandoned by the river.

It is to be noted that only large streams on the Columbia basalt have Dalles type channels. The determining conditions

for this type of river channel are (1) large volume and (2) high gradient of the stream, and (3) close and vertical jointing of the rock. Where the conditions all exist, and the stream has room to spread at high water, the type results. Where any one of them is lacking, it is not formed. The small streams of the plateau are uniformly without this feature. The large streams in most places have too low a gradient. Adequate volume and gradient, as in many rapids of the Columbia above Rock Island Rapids, fail to produce the type because the proper rock structure is lacking.

FIG. 5.—Five Mile Rapids, near lower end. Photograph taken at an intermediate river stage, looking diagonally upstream.

All Dalles-type channels are early stages in the development of a simple channel. Trenching of a central main channel eventually results and with this trenching the high water channels are gradually abandoned. By this trenching the gradient is lowered, plucking decreases, and the holes in the rock floor disappear by simple abrasion of the higher parts and perhaps also by filling of the lower. The hole 115 feet below sea-level at the head of Five Mile Rapids eventually will be filled in large part.

This leads to a consideration of some abandoned Dalles-type river channels on the Columbia Plateau north of Snake River. There are hundreds of miles of channels of this character on the plateau, none of them along present major rivers, and many of them without even intermittent streams. They constitute the "scabland" of the plateau.[1] Aside from the great width and depth of

[1] Described by the writer in *Bulletin of the Geological Society of America*, Vol. XXXIV, No. 3, and in *Journal of Geology*, Vol. XXXI, No. 8.

FIG. 6.—Detailed topography of the head of Five Mile Rapids, drawn from land surveys and soundings. Contour interval above low-water level (55 feet A.T.) is 5 feet, subaqueous contour interval is 10 feet. Contours numbered from sea-level. (After L. F. Harza, *Columbia River Power Project near The Dalles, Oregon*, Fig. 10.)

some of them, they are strikingly like those in use at the Dalles of the Columbia today. They possess the anastomosing channels about flat-topped, steep-walled rock islands, the narrows and long chutes, the cataracts, the eddy pockets, the rock basins in their floors, and the steep gradients of the whole. Figure 3 shows a small portion of one tract of abandoned Dalles channels about 8 miles south of Moses Lake. There are many more waiting to be mapped. Figures 7 and 8 show two rock basins in the "scabland" channels in another part of the plateau. Submit the Corfu sheet, showing

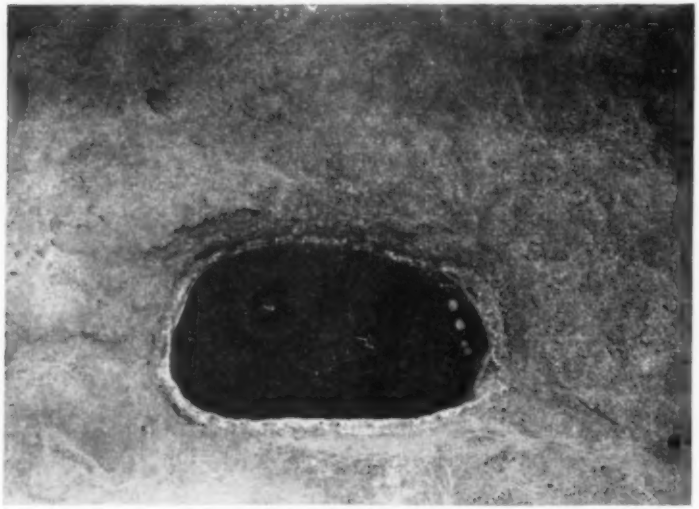

FIG. 7.—A rock basin lake in the abandoned Dalles-type river channels (the scablands) of the Columbia Plateau, near Spokane. Airplane photograph by F. H. Frost.

these channels eroded in solid rock, to any student of land forms. He must admit that they are very exceptional. He will probably add that he has never before seen anything quite like them on a topographic map. The Corfu sheet, just issued by the United States Geological Survey, is the first map to delineate adequately the Dalles type of river channel.[1]

Because of the great number and great magnitude of these features on the plateau, one is tempted to question the explanation

[1] Except Mr. Harza's map of Five Mile Rapids, reproduced in Fig. 2.

of their origin here offered. But, aside from the striking similarities to the Columbia channels near The Dalles, there are many consistently corroborative field evidences,[1] the sum of which cannot be explained in any other way. Such present-day streams as use the scabland channels of the plateau have no Dalles-type channels. They all lack the requisite volume. The ancient streams were prodigious affairs for they carried all the drainage of the Cordilleran ice sheet west of the Rocky Mountain continental divide as far as the longitude of Lake Chelan, Washington. Abrupt loss of volume,

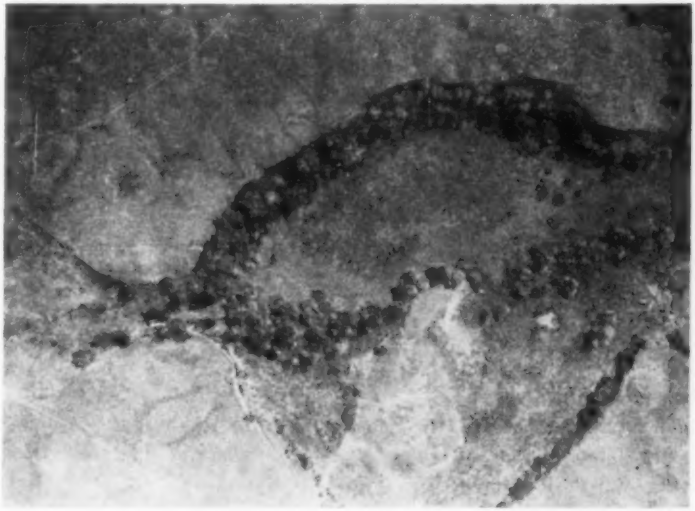

FIG. 8.—A dry lake bed in a rock basin of the abandoned Dalles-type river channels of the Columbia Plateau. A constriction of the channel, very similar to that at the head of Five Mile Rapids, is shown. Talus along the bounding cliffs is covered with shrubs and trees. Airplane photograph by F. H. Frost.

rather than deep trenching and decrease of gradient, decreed the abandonment of these Dalles-type channels. In some cases, the main channels were canyons in dimensions and probably carried all the water toward the close of the epoch, even at the height of summer melting. In other cases, annual flooding of the shallower margining channels probably occurred, similar to that at The Dalles today.

[1] Presented in detail in the writer's paper in the *Journal of Geology*, above noted.

THE VERDEN SANDSTONE

R. D. REED AND NORMAN MELAND
Palo Alto, California

ABSTRACT

The paper describes a supposed river channel deposit in the Permian Red Beds of southwestern Oklahoma. The rock differs much in lithology and primary structures from the associated strata. It contains a good many fossils, which are discussed not paleontologically, but as sedimentational data: i.e., for the light they may throw upon the conditions of deposition of the rock in which they occur. Its petrographic characteristics, especially the relations of the rarer detrital minerals, are discussed in some detail.

The results of the study are considered to show that the rock was probably deposited by a river which flowed northwestward from the Arbuckle Mountains. The abundant calcareous cement is held to have been deposited mechanically as a lime mud. The suggestion is made that the peculiar lithologic features may be due to deposition under somewhat unusual conditions; perhaps by one of the cloud-bursts that occur at long intervals in most arid regions.

In southwestern Oklahoma near Chickasha there occurs, capping a row of elongated buttes, a strikingly cross-bedded, calcareous, red sandstone. Examined by many geologists, and traced throughout its length by several, this sandstone is known to have been mentioned in print but once.[1] Because of its many peculiar features, and also because it is a well-exposed representative of the interesting "shoestring sands" of the Mid-Continent oil district, a field and laboratory study of this formation was undertaken a year and a half ago and has been pursued at odd moments since that time. Owing to the impracticability of carrying the work farther in the immediate future, it is proposed to give at the present time a description of the formation and a preliminary discussion of the problem of its origin.

DESCRIPTION OF THE FORMATION

From a point a few miles northwest of the village of Verden, shown on the map, Figure 1, the above-mentioned buttes extend in a nearly

[1] F. Reeves, "The Cement Oil Field," *U.S. Geol. Survey Bull. 726–B*, p. 61.

straight line toward the southeast. Seen from a distance, they much resemble parts of a great railway embankment. They rise, in general, 75 to 100 feet above the level of the small streams that separate them. The tops of the buttes are a little lower than the summits of the highest hills of the region; in fact, some of the higher hills are penetrated by the sandstone bed which elsewhere caps the buttes. In such localities, one may learn much about

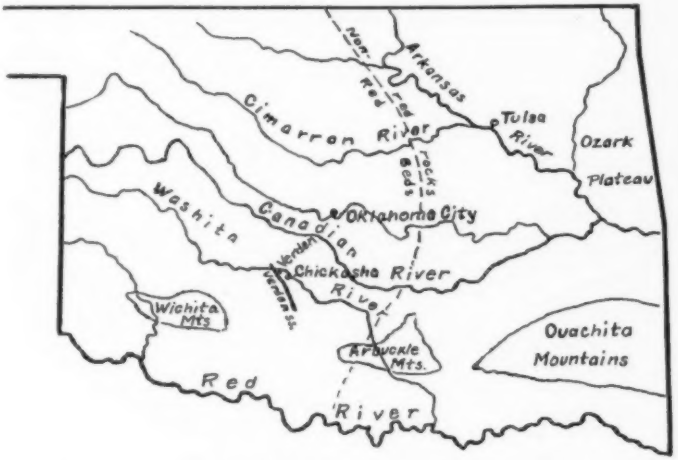

FIG. 1.—Index map of part of Oklahoma, showing location of Verden sandstone outcrops.

the dimensions and stratigraphic relations of the formation, which will here be called the Verden sandstone[1] (Fig. 2).

This sandstone is inclosed in gypsiferous shales and fine-grained sandstones of Permian age. Its upper surface is flat, and it appears to be thicker in the middle than at the sides. It reaches a thickness of 10 feet, is 1,200 feet in maximum width, and as exposed at present is somewhat more than 30 miles from end to end. It occurs about 75–100 feet below the base of the sandy phase of the Whitehorse sandstone, which has been fully described by Reeves.[2]

[1] N. Meland, unpublished thesis, University of Oklahoma.

[2] *Op. cit.*, pp. 51–61.

It is thus seen to be merely a minor feature of the great Red Beds series of the Southwest.

With a trend sensibly parallel to the strike of the associated beds, the Verden has, of course, no perceptible dip. For this reason the hills capped by it are everywhere of approximately equal height (Fig. 3). Careful surveying would no doubt show slight variations from the horizontal, but as these would obviously have no necessary relation to the initial dip of the beds, no such work has been considered necessary for the present study.

Lithology.—From the presence of numerous small, angular fragments of white and reddish chert, which have weathered into

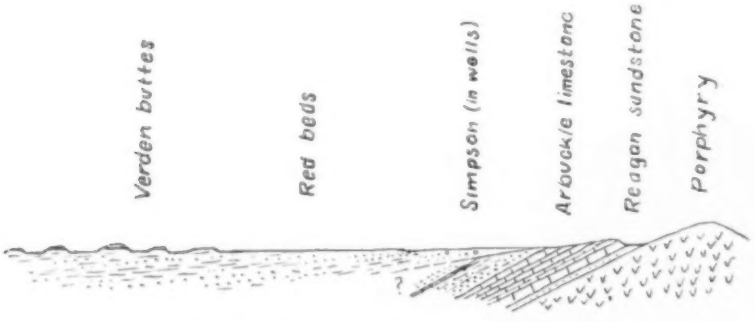

FIG. 2.—Diagrammatic structure section to show relation of Verden sandstone to Arbuckle Mountain formations at present time. Horizontal scale about 20 miles to 1 inch.

relief, the Verden rock has everywhere a rough, speckled appearance. These fragments, which measure 3–4 mm. in diameter or less, are scattered rather uniformly over most parts of the surface, and indicate one prominent characteristic of the rock—its poor sorting. This feature is shown further by the scarcity of well-defined bedding planes in most outcrops, and by the absence of beds of clean sand and shale from the formation.

Because of the lack of beds of clean shale, mud-cracks are hardly to be expected, and none have been observed. Definite ripple marks are also rare, although many irregularities in the surfaces of the beds exist. The chief original structure, in fact, is the cross-

bedding, which is all but universally present. The greatest measured thickness of a cross-bedded stratum is 7 feet (Fig. 4). The cross beds dip uniformly about 17°–20° toward the northwest. They stand out in ribs along the edges of the beds, and in many places even along the tops. In no instance was the direction of dip seen to vary noticeably from the direction given.[1]

In addition to the chert grains, the chief constituents that are visible to the eye are spherical, frosted grains of colorless quartz, and occasional angular pebbles of grayish or reddish shale. There

FIG. 3.—The end of an elongated butte, seen from one side

is also an abundance of reddish cementing material which in places is so limy that cleavage surfaces of calcite may be seen on a fresh fracture.

Fossils.—In spite of the somewhat unpromising appearance of the sandstone, it has yielded many fossils of a few species. Of the invertebrates, the most abundant are small pelecy pods about one-fourth inch in longest dimension. There are occasional gastropods of similar size. All the fossils are present as molds, the original shell substance, so far as observed, being entirely gone.

[1] Dr. J. W. Beede states in a personal letter that he found irregularity in the direction of dip of the cross-bedding in a single locality, which happened not to be closely examined during the present study. The occurrence is likely to prove of much importance in the interpretation of the conditions of deposition of the formation.

Some other facts about the fossils, which may possibly have a bearing on the origin of the formation, were noted incidentally and may be recorded here. In view of the small size of the shells, and their presumably fragile character when deposited, it appeared remarkable that broken shells could not be found. In all cases, however, the two valves of the pelecypod shells have been broken apart. All of them, with rare exceptions, lie in the rock with their concavities downward, the position in which they would offer the least resistance to a current passing over them.

FIG. 4.—Cross-bedding in the Verden sandstone, west of Chickasha, Okla.

Although two or three separate paleontological investigations of the Verden fauna have been undertaken, the results appear not to have been published. It is fortunate, therefore, that Dr. J. W. Beede has kindly contributed the following additional facts in regard to the occurrence and nature of the fossils:

> The fossils . . . . are probably not strictly fresh water forms.
>
> . . . . The same species are found at Whitehorse Spring, Oklahoma . . . . [along with] brachiopods, deltopectens, etc. The same species occur in the rocks exposed just east of the old post office of Dozier, Collingsworth County, Texas, in a higher horizon, where they are also associated with brachiopods.
>
> I have seen no brachiopods in the sandstone in the Chickasha region and it is very probable that that fauna may have lived in brackish or nearly fresh

water in the Chickasha area. It cannot be said that it is impossible that these mollusks might have lived in fresh water.

The sandstone at Whitehorse Spring is of the same character as that near Chickasha, and the same thing is true of the sandstone containing the Collingsworth County fauna. . . . .

There is not a specimen of fossil to be found in the associated beds in the immediate region of this [Verden] outcrop.

Petrographic characters of the Verden sandstone.—The microscopic features of the sandstone have been studied both in thin sections and in mounted grains. The thin sections show that the cement is dominantly calcite, and that it is at least equal in quantity to the other materials of the rock. The detrital grains are scattered so thinly through the cement that they rarely if ever are seen to touch one another. In some places the red coloring matter appears as circular rings in calcite areas, as if it had begun to be aggregated into concretions. The detrital minerals commonly observed are quartz, chert, and occasional microcline.

As a preliminary step to a study of the grains by themselves, samples of the sandstone were broken down by solution in dilute hydrochloric acid, the ferruginous matter loosened by boiling in the same acid, and the detrital grains washed clean by repeated suspensions and decantations. The grains were then separated into light and heavy crops by means of bromoform. Observations made during these operations showed that the calcite makes up from 50 per cent to 75 per cent of the rock, which might therefore be called an arenaceous limestone. Of the non-calcareous material nearly half is fine mud of a bright red color. The sandy portion is whitish in color and so poorly sized that screening through a Bureau of Soils standard set of sieves gave in one instance nearly equal amounts of the various grades. The sorting appears to be somewhat better in the rock of the more northern outcrops.

Bromoform treatment of a few samples from different outcrops has given uniformly small crops of accessory minerals, all very fine-grained. The grains are so small, in fact, that in spite of their high density most of them appear to have been decanted with the mud in some of the earlier experiments. Later work, however, in which larger samples were treated with great care, gave enough of

the heavy residue to afford important clues to the possible sources of the sandstone.

The percentages of the heavy crop that were furnished by the various mineral species were estimated by counting several hundred grains as they were propelled across the field by a mechanical stage. Similar estimates are included in the accompanying table for a specimen of Simpson sandstone from the western part of the Arbuckle Mountains, and for a specimen of Canadian River sand taken from a point near Norman, Oklahoma.

TABLE I

PERCENTAGES OF HEAVY MINERALS IN SOME SEDIMENTARY ROCKS OF THE CENTRAL UNITED STATES

	Verden	Simpson	Canadian
Zircon	31.2	57	5
Rutile	.2	1	.....
Muscovite	2.4	.....	Present
Ilmenite-leucoxene	3.0	.....	2
Black opaque	21.4	3	40
Turbid, whitish	19.8	.....	9
Tourmaline	14.0	34	2
Garnet	5.4	2	6
Epidote	1.8	2	12
Amphibole	.2	1	2
Staurolite	Present	.....	1
Others	0	0	21

Since only a little work on the heavy minerals of the Mid-Continent sedimentary rocks has been done, it was considered desirable to study a few samples from other formations for comparison. The Simpson formation was selected because it contains more clastic material than the other Arbuckle Mountain rocks that were probably exposed to erosion during Permian times. The Canadian River sample was studied with the idea that it might throw a little light on the sort of materials that a Permian river might have brought from the Paleozoic Rocky Mountains and deposited in central Oklahoma. The Canadian River rises in the Rocky Mountains of northern New Mexico and flows for several hundred miles through Tertiary sands and gravels derived from those mountains. The evidence to be gained from such a small

amount of investigation could not, of course, be expected to be more than suggestive.

Inasmuch as the table fails to show many of the facts about the heavy minerals that appear to be most significant, some notes will be added.

Zircon.—Both the Verden and Simpson samples have high percentages of zircon. This fact is much less striking, however, than the high percentages of zircon grains in both that are nearly spherical. About one grain in fifteen shows fair crystal form. In the Canadian River sand, on the other hand, a much larger percentage of the relatively few zircon grains shows crystal faces.

Muscovite.—The specific gravity of muscovite is so near that of the bromoform used, and its shape so adverse to rapid subsidence, that the low percentages of that mineral showed by the table have no special significance. From other studies, however, it appears that muscovite is actually not very abundant in most of the samples studied.

The opaque minerals.—Ilmenite is so listed when a black grain showed a whitish alteration product considered to be leucoxene. "Black opaque" covers, presumably, ilmenite not so altered, chromite, perhaps some magnetite, and even, it is likely, some thick, black tourmaline grains in the Verden sample. Since the identification of all these minerals is doubtful, it is considered best to list them so that the fact is evident. The identity of the turbid, whitish grains is likewise unknown. Some of them may be feldspar, although no recognizable feldspar grains were included.

Tourmaline.—Of all the heavy minerals the tourmalines are considered to show the greatest similarity between the Simpson and Verden formations, while they are very scarce in the river sand. Not only are the percentages of the mineral high in the two older rocks, but the grains are identical in the two as to shapes, sizes, and colors. On the average, a tourmaline grain has an area in the slide about five times as great as a zircon. The larger grains all show circular or elliptical shapes, a few of the smaller ones being prismatic crystals. An occasional grain fails to show the characteristic pleochroism, but gives a good uniaxial, negative interference figure. In color there is great variety: dusky gray, black, yellow,

orange, brownish, red, blue, and green varieties occurring in both formations.

Garnet.—The garnets commonly observed are colorless or a pale flesh color, but occasionally reddish. In some of the Verden samples there have been observed large numbers of irregular, pitted grains having the optical properties of garnet. The pitting may be due to the development of a cleavage or parting, or possibly to some sort of intergrowth. Whatever its nature, it is distinctive and apparently uncommon, having been observed in no other rocks studied except the Simpson.

The situation in regard to the heavy minerals may be summarized as follows: all of the Verden minerals have also been found in the Simpson formation; some of the Verden minerals have peculiarities that have not been observed in some hundreds of samples of rocks collected in other parts of the United States, but all of them have been found in the samples taken from the Simpson formation; finally, in a study of several samples of Simpson sandstones and limestones, only one or two rare minerals, including a pink corundum (?) and an unknown blue, uniaxial mineral, have been seen without also being found in the Verden sandstone.

SUMMARY OF THE CHARACTERISTICS OF THE VERDEN SANDSTONE

The Verden sandstone has thus proved to be peculiar in various respects, especially when compared with the associated beds. Its shape and dimensions are unusual. Its lithology is such that a fragment of it can be readily distinguished from fragments of other rocks of the region in which it occurs. Its fossils, both vertebrate[1] and invertebrate are peculiar, its cement is unusual in kind and amount, and even the rarer accessory minerals are distinctive to an unusual degree.

As suggested in the beginning, the formation recalls the "shoestring sands" of the eastern Kansas and Oklahoma oil fields.[2]

[1] Some peculiar possible footprints found in this sandstone are worthy of mention, though this is not the place to attempt a description of them.

[2] J. L. Rich, "Shoestring Sands of Eastern Kansas," *Bull. Am. Assoc. Pet. Geol.*, Vol. VII (1923), pp. 103–13. Hinds and Greene, *Bulletin XIII, Mo. Bur. Geol. and Min.*, chap. iii; W. R. Berger, "Hogshooter Gas Sand," *Amer. Jour. Sci.*, 4th series, Vol. XLVIII, pp. 189–94.

So far as these have been studied, however, it appears that they resemble the Verden chiefly in form. None of them has been shown to possess such an assemblage of minor characteristics as have been found in it.

DISCUSSION OF THE PROBLEMS OF THE SANDSTONE

In spite of the many distinctive characteristics of the Verden sandstone, the field and laboratory study already devoted to it has not been sufficient to suggest with any certainty the solution of the problem of its origin. The data secured seem to throw light on the source of the Verden materials, however, and are somewhat suggestive as to the manner of their deposition.

Assuming for the moment that this peculiar sandstone was deposited, as it appears to have been, in a river channel, and adopting the usual views as to the distribution of the higher land areas in central North America during Permian time, one will see that the Verden River probably flowed either from Grabau's "Rocky-montana," near the present Colorado Rocky Mountains, or from the ancestral Arbuckle or Ouachita Mountains. With these two possibilities in mind, the Verden materials will be discussed under the following heads: quartz grains, chert grains, shale pebbles, heavy minerals, cement.

Quartz grains.—The most striking feature about the quartz grains is their rounding. When compared with the angular chert fragments, the equally angular shale pebbles, and the unworn shells, the quartz grains suggest that they may have been derived from a sandstone, the grains of which were already rounded. The suggestion is especially strong because there is little evidence of wind-drifting of materials at the time when the associated gypsiferous shales and sandstones were being laid down. If the grains had come from the Rocky Mountains, which were furnishing angular granitic materials to the Lyons and Fountain formations about this time, it is likely that the rounded grains would have been mixed with a good proportion of angular grains, derived also directly from the granite. If, on the other hand, the material came from the Arbuckle Mountains, the most likely source of quartz grains would be the Simpson sandstone.

This formation, as is well known, consists in its coarser phases chiefly of well-rounded quartz grains, many of them with secondary enlargement. Since the latter feature has not been observed in the Verden grains, the evidence is not so good as it would otherwise be. It is possible, of course, that the Verden River was bringing materials chiefly from one of the districts, of which a few are known, where secondary enlargement is not common in the Simpson formation. It is also possible, though apparently not likely, that the crystal faces might have been worn off, or the angles dulled so that they have not been noticed, during the transportation of the grains. It is perhaps most likely that the secondary enlargement of the Simpson grains post-dates the Permian period. In spite of all these possibilities, it must be recognized, however, that this dissimilarity between the Simpson and Verden quartz grains tends to weaken the theory that the former are the source of the latter.

Chert grains.—That the Arbuckle Mountains are an adequate source of chert grains will be appreciated by anyone who has observed the thick Seminole conglomerate north of those mountains. It will be evident also upon consideration of the fact that several thousand feet of cherty limestones are exposed in those mountains. In comparison with them, the Colorado Rocky Mountains appear to be a rather poor source of chert. Not only is there little chert in the Canadian River sand, but the western Oklahoma Tertiary gravels show only about 1 per cent of chert pebbles.[1] In addition, since observations in many districts, as for example in the Seminole conglomerate belt in east-central Oklahoma, have shown that chert grains tend to be rather rapidly eliminated from a mixture of chert and quartz grains, it would seem strange that such a mixture, coming from the Rocky Mountains, should have been deposited in central Oklahoma as a mass of angular chert and spherical quartz grains.

Shale pebbles.—It is probable that the shale pebbles, which are much larger than the other detrital materials and are angular, were simply pieces of dried mud picked up from the bottom or sides of the depression in which the formation was deposited.

[1] R. S. Knappen, oral communication.

Heavy minerals.—In the absence of exhaustive data in regard to the heavy minerals of the rocks that might have contributed to the Permian beds of Oklahoma, the evidence from the heavy minerals of the Verden cannot be considered conclusive. The facts stated in a previous paragraph, however, are certainly very suggestive. The agreement between the heavy mineral assemblages of the Verden and Simpson formations is so surprisingly complete, and extends to so many minute details, such as the shapes and many hues of the tourmalines, and the peculiar pitting of the garnets, that the discovery of any reason for the agreement, other than that the one is the source of the other, appears a difficult task.

The cement.—The source of the calcite, and the conditions of deposition necessary to account for its abundance, constitute an interesting problem in themselves. That the cement originated in a manner similar to kunkar, or that it was deposited secondarily by circulating waters, are possibilities, perhaps, but hardly more, since they fail to account for the absence of calcite in the associated beds. The texture of the rock, as observed in thin sections, is likewise difficult to harmonize with such an origin. It is, in fact, only when one assumes that the Arbuckle Mountains are the source of the Verden detritus that he finds a satisfactory explanation of the puzzling cement. This explanation may now be sketched.

The valleys in the Arbuckle Mountains have along their bottoms many blocks of limestone, and many fragments and masses of travertine. Every flood probably picks up and carries along great quantities of these blocks. The travertines appear to be especially liable to be ground up rapidly, but even blocks of hard limestone are known to disappear before being carried far by a flooded river. If the limestone fragments were very abundant, however, as they are in the Arbuckle valleys, it is unlikely that solution could be active enough to account for the disappearance. It is more likely that the blocks would be ground finer and finer until they became lime mud. This mud might then be deposited like mud of any other kind, and might thus come to imbed and surround the detrital grains as shown by the Verden thin sections.

The red mud of the Verden cement is a problem of the Red Beds in general rather than of the Verden sandstone in particular.

Without discussing the matter at length, therefore, it may suffice to call attention to one of the most interesting suggestions in regard to the broader problem. Dr. Beede[1] has supposed that the color of the Oklahoma Permian rocks may be due to red mud derived from the chemical decomposition of immense masses of limestone that made up the Wichita and Arbuckle mountains in later Paleozoic time. Whether or not the source is to be considered adequate for the whole body of Permian red rocks, it must be obvious that it would account nicely for the red mud found in the Verden sandstone.

When all the evidence is considered, therefore, it appears that the Arbuckle Mountains are a much more likely source of the Verden materials than the Rocky Mountain region. If the sandstone is a river deposit, however, its location and the direction of dip of the cross-bedding make it all but certain that the Arbuckle Mountains were the source. Then why, it may be asked, should one go to such lengths to demonstrate a point so obvious?

THE TIDAL HYPOTHESIS

The answer is suggested in the following quotation: "The presence of small marine shells [in the Verden sandstone] and the apparent upstream cross-bedding suggest that a strong tidal current flowed up this stream from the sea."[2]

As a result of his study of the Cement district, a few miles southwest of the Verden district, Reeves was led to adopt the hypothesis suggested in this quotation to account for the origin of the formation herein named the Verden sandstone. The whole passage should be consulted, as well as the discussion of the Whitehorse sandstone, which was the chief subject of his study. It will be practicable here to present only a brief sketch of the conditions assumed in the hypothesis, and to confront them with the facts brought out by the present investigation.

The hypothesis assumes a subsiding delta flat in central western Oklahoma, across which the distributaries of the Verden River

[1] J. W. Beede, "Origin of Oklahoma Red Beds," *Science*, New Series, Vol. XXXV (1912), pp. 348–50.

[2] F. Reeves, *op. cit.*, p. 61.

wandered as they built up the shale and sandstone formations now found there. Toward the southeast the river emptied into a sea, which must, of course, have been bounded on its other side by the Arbuckle Mountains, less than 40 miles away. Concerning this sea one probable deduction of interest in the present connection may be made: Since the beds inclosing the "channel deposit" are all fine-grained, the bottom of the sea, at least near the mouth of the river, was probably covered chiefly with mud and fine sand. It is true that shorelines and currents may be imagined which might account for the presence of some coarser materials from the Arbuckle Mountains along with the finer debris. That all of the sea-bottom sediment should show evidence of derivation from the Arbuckle Mountains, however, the tidal hypothesis, with its assumption of southeastward flowing rivers, would lead nobody to expect.

In favor of the tidal hypothesis the passage cited above gives two reasons, the presence of small marine shells and the apparent upstream cross-bedding. The second reason will be discussed first.

Does the cross-bedding dip upstream?—Why does the cross-bedding appear to dip upstream? The context shows the reason to be that the overlying Whitehorse sandstone appeared to have been derived from the west, and the same conclusion was applied to the channel deposit. It is believed by many students of the Oklahoma Permian rocks, however, that they represent an interfingering of materials from that source with others derived from the mountains to the south and southeast. If this contention is correct, it will be evident that only the Verden itself and the beds at exactly the same horizon are competent to give testimony concerning the direction from which it was brought. No amount of evidence that rocks a hundred feet stratigraphically higher came from the west should be considered sufficient to demonstrate the same conclusion for the Verden sandstone.

The presence of the shells.—The presence of small, unbroken, probably marine shells, the first of the reasons given for the tidal hypothesis, is certainly one of the most puzzling features of the formation. It appears to be sufficiently puzzling, in fact, even on the theory that it is considered to prove. The hypothesis, in short,

requires one to believe that a tidal current picked up from the sea-bottom masses of chert and quartz grains and millions of delicate, thin shells, mixed them thoroughly together, transported some of them more than 30 miles, and deposited them without grinding any of the shells to pieces. Without pronouncing such a phenomenon impossible, one can scarcely refrain from attempting to devise a gentler method of introducing the shells into the deposit.

Some of the difficulties of the tidal hypothesis.—Against the tidal hypothesis, several arguments may be adduced. One of them is the difficulty, already suggested, of accounting for the presence of so much coarse material on the bottom of a sea to which the main river was demonstrably carrying only finer material. A more damaging argument may be drawn, however, from the facts already stated in regard to the many constituents of the channel deposit that appear to be peculiar to the Arbuckle Mountains, and the absence of any that cannot be easily duplicated there. If the Verden River flowed toward these mountains, a complex and ingenious theory will apparently be needed to account for this fact in a plausible manner.

The cross-bedding itself appears to be more easily explained as the result of fluviatile than of tidal action. Assuming tidal action, one may ask why, during the whole time of the deposition of the channel filling, the river never developed sufficient energy to cause a little cross-bedding in the contrary direction. And if a reason for the failure of the river can be found, why did not the ebb of the tide occasionally impress itself upon the deposit? Two-way cross-bedding, it is interesting to note, is considered by Kindle a characteristic of tidal deposits.[1]

Deposition by a tidal current therefore fails to furnish a perfectly natural and satisfactory explanation of this peculiar deposit. Deposition by some sort of river action appears to be the only other reasonable explanation, and may be briefly considered in its turn. To a considerable extent, the arguments against the tidal hypothesis are arguments in favor of the river hypothesis, and need not be re-stated. In the case of the fossil shells, however, this generalization does not hold, and the possibilities will have

[1] E. M. Kindle, "Characteristics of Marine Clastics," *Bull. Geol. Soc. America* (1917), p. 915.

to be discussed at greater length, perhaps, than the paucity of the relevant facts would seem to justify.

The problem of the shells.—It has been suggested above that the presence of the marine shells in this river channel deposit is not adequately explained even by the tidal hypothesis in its present form. To put the fluviatile hypothesis on an equal basis it is not necessary, therefore, to show that it explains the presence of the shells simply and naturally. If it can merely be shown that their presence does not actually preclude that hypothesis, the choice between the two will have to be made from other considerations.

When one considers the problem from the standpoint of the fluviatile hypothesis, he finds at least three possible explanations of the presence of the shells. First, of course, comes the possibility suggested above that the fossils are not marine. The absence of undoubted marine forms from this fauna, and the presence of such forms in its other known occurrences, might mean that the water in which the mollusks lived in this area was not sea water. It might mean, in fact, and this is the second possible explanation, that the mollusks lived, not in fresh water, but in a salt lake somewhere upstream from the part of the channel now known. Desert salt lakes, as Walther observes,[1] may come to be occupied by marine organisms by many different methods; as many, probably, as are used by land organisms in reaching an isolated oceanic island.

On the assumption that the mollusks are truly marine, the only course is to account for their presence in an inland deposit by a method that involves as little rough usage as possible. If the low coastal plain adjacent to the Verden channel was subject to strong on shore winds during a part of the year, it might have been periodically flooded with sea water, perhaps for many miles inland, somewhat after the fashion of the Rann of Cutch at the present time. The carrying in of shells by such a flood, loaded with little abrasive material, would seem to account for the state of preservation of the Verden shells more readily than the tidal theory in the form discussed above. The fact that these shells appear to have been, as already shown, loose, single valves when they were deposited is consistent with the proposed hypothesis.

[1] Johannes Walther, *Das Gesetz der Wüstenbildung* (page reference not available.)

The fact that no similar shells are found in the beds associated with the channel sand is a difficulty on the hypothesis that the mollusks lived in the sea. One would expect that shells would have been scattered widely over the low shore by the floods. If they were so scattered, however, they must have been destroyed either during or after deposition everywhere except in the channel itself. Dr. Beede's statement, quoted above, to the effect that these species appear to be limited to similar—that is, presumably, calcareous—sandstones suggests that the abundance of calcareous mud mixed with the channel sand may have prevented the destruction of the shells during deposition, or their removal by solution later.

With all these possibilities at hand, it is evident that the mere presence of the marine shells cannot be considered adequate proof of the tidal hypothesis. And if this conclusion is granted, it will be seen that that hypothesis has very little left upon which to stand. Its failure leaves the theory of deposition by a river current practically the only available explanation, and for the purpose of the present discussion that theory will be adopted without further argument.

The fluviatile hypothesis may assume many forms, however, and the facts do not permit one to choose certainly among them. Was the channel filled by a permanent stream, or by a large number of floods along an intermittent stream, or possibly by one or a few unusual floods along such a stream?

THE FLUVIATILE HYPOTHESES

A permanent stream is unlikely, perhaps, but not impossible under the conditions that appear to have existed in central Oklahoma in mid-Permian time. A permanent stream that never varied, however, and thus deposited only unsorted, sandy lime-mud, with no beds of clean sand or mud, is a still more unlikely phenomenon. On the other hand, if the deposit was due to many floods, where are the mud beds deposited during the subsiding stages of the floods? And the mud cracks and gypsum lenses developed during the dry periods? And why should this channel filling differ so markedly from the associated beds, which must themselves have been formed chiefly as channel fillings?

The difficulties of understanding these and other peculiarities of the deposit led to the consideration of another hypothesis, which, like those already discussed, can neither be proved nor disproved with the available data. It has the merit of being the only hypothesis that came to mind first during the field investigation. It will therefore serve at least to convey to the reader the kind of impression that the channel sand is capable of making upon an observer. According to this hypothesis, the Verden channel, a distributary of a desert river, was filled by an exceptional flood of the sort that Walther and others have described as occurring at rare intervals in arid regions. It appeared that this hypothesis might account for the uniformity of the materials and of the cross-bedding, for the general absence of shales and similar evidences of irregularities in deposition, and for the fact that this particular channel filling differs so markedly from the associated channel fillings. But on the other hand it seems an open question whether a flood of the kind assumed is mechanically competent to make such a deposit as the one under consideration. Since no modern analogue can be mentioned at present, the hypothesis is put forward merely as a speculation.

In conclusion a few of the more interesting facts and inferences in regard to the Verden sandstone may be tabulated.

1. The detrital materials are entirely of kinds that would be expected to come from the Arbuckle Mountains.

2. The calcite cement is most readily explained on the hypothesis that it was introduced as lime-mud, derived from the mechanical disintegration of the limestones of the Arbuckle Mountains, or of travertine derived from them.

3. It is considered likely that the sandstone was deposited by a river current rather than by a tidal current.

4. Certain features of the sandstone suggest rapid and continuous deposition, as by a single unusual flood.[1]

[1] Since the field work for the present paper was finished, the Chickasha district has experienced an oil boom. Because of this fact a number of geologists have devoted far more time to the field study of the Verden and associated formations than the writers were able to give to it. While the results of this more intensive field study are known, in part, to the writers, and some of them have been verified, no attempt has been made to include them in this paper. It is hoped, however, that these facts will soon be made available by their discoverers.

REVIEWS

Bau und Entstehung der Alpen. By LEOPOLD KOBER. Berlin: Gebrüder Borntraeger, 1923. Pp. 283, figs. 102, pls. 8.

This new synthesis of Alpine growth and tectonics is dedicated to Kober's theory of two-sided orogeny. Kober's belief is that the normal orogeny, instead of manifesting itself in a single mountain chain, overfolded and overthrust from one direction, is double, consisting of two chains or groups of chains near the margins of the deformed belt, which are thrust and overfolded in opposite directions, while the middle zone undergoes less intense deformation. As the axial planes of the overturned folds and the planes of the thrust faulting dip inward under the mountains on the two outer margins, the orogenic block takes the form of a wedge apexing downward, and recalls the wedge theory of the reviewer.

Kober's most distinctive contribution lies in recognizing the Alpine and Dinaric ranges as opposite phases of the same orogeny. This has in turn led to a splendid synthesis of the whole Mediterranean complex. The northern or Alpine chain runs from the Betic Cordillera across central Spain and then follows a sinuous line through the Pyrenees, Alps, Carpathians, Balkan ranges, Caucasus and on across Central Asia. Structures overfolded and overthrust toward the north, or bordering forelands, characterize these mountains. The southern or Dinaric chain comprises the Atlas, Apennines, Dinaric Alps, the ranges of Greece, and the Greek isles, of Taurus and Iran, and onward to the Himalayas. Structures overfolded toward the south, or bordering forelands, prevail in this southern strip. These are the Randketten or marginal chains of the orogen. Between them lies a zone of varying breadth which has undergone much less pronounced deformation (*Zwischengebirge*). This middle zone is wider in the western Mediterranean, Hungarian region, and central Asia Minor. It disappears altogether as a surface feature where the Alps and Dinarides come together near the northern end of the Italian peninsula, and where the Dinaric and Grecian chains of the southern strip are crowded against the Balkan ranges of the northern marginal string. This has been presented before in *Bau der Erde* which appeared in 1921, and seems a great advance over the earlier alignments of these tectonic units by Suess, Termier, and others.

Early in his book Kober brings out in considerable detail the decken system of the Alps, adhering rather more to the original conception of attenuated recumbent folds than to later tendencies to replace much of the overfolding by overthrust faulting. These decken are drawn out toward the north. The order of development progresses from inner to outer. Later he shows that decken structure characterizes also the Dinaric chain, with both similarities and differences. The two chains are similar in that the overfolding in each has proceeded from inner to outer; in each case the movement was outward—in the Alps toward the north, in the Dinarides toward the south. But the Dinarides are on a smaller and less declared scale. Thus the ensemble is a two-sided orogeny with one side more strongly developed than the other. Since the whole is a composite of several periods of diastrophism, and as the Dinarides have finally come to be overthrust to some extent upon the Alpine folds, simplicity and symmetry are not the rule.

The Alpine-Dinaric boundary begins with the zone of Ivrea, follows past the Italian Lakes and along the Adda to Tonale, and continues eastward to the end of the mountains. Extensive intrusions characterize this belt, occurring here and there in a zone about this dividing line. Kober says that these intrusive masses are not closely related to the tectonics. They cut through the decken and so are younger than the principal mountain building, but they are still assigned to the Oligocene. It would seem to the reviewer that one might perhaps well assign them a closer genetic relationship to the folding processes. It has been pointed out[1] that these, and analogous intrusions in various other orogenies, are located in the middle portions of deformed wedges where the deformation has reached greater depths than it has in the shallower overfolded and overthrust marginal sheets, which have been shoved onto and toward the borders of the orogenic wedge.

Kober's general philosophy is that decken form only where a geosyncline has been. The geosyncline grows steadily deeper and great masses of sediment accumulate. Rising folds (embryo decken) form islands which divide the main geosyncline into separate troughs. The folds push forward into the troughs, pouring their depositional débris into the depths before them. Thus arise the breccias and conglomerates which form obstructions in the path of the forward-pushing mountains. In the inner portions of the geosyncline the main mountain building sets in. From these it goes farther and farther outward over the fore-

[1] "Vulcanism and Mountain Making—A Supplementary Note," *Journal of Geology*, Vol. XXIX (1921), pp. 166–72.

lands. The whole is a squeezing of the geosynclines between the more resistant masses of the forelands which are overridden by the advancing rock masses. Thus the normal orogeny is two sided.

In the main orogenic trough is the great decken building. Here lie great masses of rock piled over one another constituting two or three times as much rock as formerly occupied the same space. Here the metamorphism is most intense. Kober believes that only a small portion of the involved rock masses are apparent at the surface; the greater part lies, in consequence of its weight, sunk in the trough. According to Heim only one-fourth to one-fifth constitutes true mountains at the surface, the rest being submerged. Thus the gravity deficiency of the Alpine trough is explained.

The gravity anomalies are all in the diastrophic equation, but just how is not certain, for no conclusive results have been obtained. The general distribution of gravity in the Alps shows a large deficiency of mass increasing from the outer margin toward the inner zone and culminating in the midst of the mountain chain, and then diminishing toward the root zone. In the Italian Lakes region this gives way to a positive excess of gravity. The gravity deficiency is greatest beneath the St. Bernard and Dent Blanche sheets. This is where the piling up of decken has been greatest, reaching, according to Argand, down to depths of 22 kilometers. This distribution of gravity has been explained as a necessary consequence of the division of the Alps into decken land and root land. In the region of the roots deep masses of the crust have come up yielding high-density figures, while in the region of the decken they have been pressed down and deeply buried beneath lighter surface rocks. But this is not particularly the work of Kober.

To these two recent books by Kober students of tectonic problems are greatly indebted, for they present, in the opinion of the reviewer, a far more satisfactory concrete picture of the outstanding features of a normal orogeny than most workers in that field have in mind. Probably all compressional mountain systems have not developed in the way sketched by Kober, but many of them clearly have, which is sufficient to uphold the hypothesis. But, on the other hand, it would seem that in selecting his pair of opposing marginal ranges, Kober has in certain cases chosen ranges too distant from one another and thus made his units too large. The North American Cordillera is a case in point. Kober has designated the Rocky Mountain system as the eastern border range and the Pacific Cordillera as the western border chains of a single orogeny. But, as is well known, the times of deformation on the two sides were

quite different, indicating apparently two separate orogenies. Nevertheless distinct manifestations of wedge type of structure have been noted in each of these two systems and have already been incorporated in the wedge theory of mountain building. In the northern Rockies, the easterly dipping thrust plane at the western base of the Mission Range of Montana coupled with the westerly dipping Lewis overthrust plane along the eastern border of the Rockies has been interpreted by R. A. Wilson to substantiate the wedge theory, while farther north, in Canada, the easterly dipping structures discovered along the east wall of the Rocky Moutain trench, by F. P. Shepard, have been similarly interpreted by him. The eastward-dipping Willard overthrust, in the west front of the Wasatch, has long been suspected of having similar import.

In the Pacific system overturning and thrusting in opposite directions has been noted in the southern Sierra Nevada and in Nevada beyond by C. R. Longwell, while C. L. Baker writes that in the San Emigdio Range, which connects the Sierra Nevada with the southern Coast Range of California, the strata on the south flank are overturned to the south, toward the Pacific, and on the opposite north flank there is a great overthrust toward the north, the San Joaquin Valley. Finally, a reconnaissance across the Chugach Range of Alaska in 1919 led the reviewer to the belief that here was perhaps one of the best opportunities yet recognized for further study of the workings of the wedge principle. Near the coast the cleavage and axial planes of the folds in this east-west trending range dip to the north inward under the mountains at angles between 50° and 60°, while toward the inland margin of the same chain, the dip of such structures changes to the south. The units in these cases are different from those selected by Kober to support his theory, but the principles involved are in the main similar to those which he is urging.

These two remarkable works of Kober's are a very important forward step toward a comprehensive philosophy of the nature and methods of mountain building. They give us a concrete working picture of what has taken place in that perplexing assemblage of Mediterranean mountain systems which culminates in the almost incredible structures of the Alps, and they give us also a most promising orogenic type model to apply to some of the other mountain systems of the globe.

R. T. C.

Die Grundlagen der Alpiner Tektonik. By F. HERITSCH. Berlin: Gebrüder Borntraeger, 1923. Pp. 259, figs. 33.

The Principles of Alpine Tectonics may suggest principally European geology, but the Alps are such an extraordinarily declared example of mountain building that the principles and theories of their formation involve in an important way the most fundamental concepts of earth diastrophism. Because their structure is far more complex than that of most other ranges and more difficult of interpretation, the Alps may not point so clearly to their mode of origin as some other simpler mountain systems, and so in consequence studies based on them alone may the more easily lead to erroneous conclusions. And yet probably no large mountain system has been so carefully worked out in detail by so many competent geologists as the Alps. So it is that any authoritative philosophical treatise on Alpine structures and theories is of prime interest in the general field of tectonics.

The opening chapter deals with geosynclines and foredeeps, and lays the foundation for a discussion of orogenic and epeirogenic movements. Chapters ii and iii are devoted to the principles of folding and discussions of related phenomena. Then follows the main chapter of the book on the building of the Alps. In this much more attention is given to the eastern Alps (the particular field of the author) than to the western. The Swiss geologists explain the Helvetian zone by recumbent folds. Heritsch believes that these masses are controlled in large and in small by movements in the bedding planes—a sort of pervasive shear apparently.

Heritsch throws the whole force of his book against the famous decken theory which, starting with Marcel Bertrand, was strongly developed by Schardt, Lugeon, Heim, Haug, Termier, Kilian and many others, till it has come to be one of the wonders of modern geology. Many arguments are adduced to show that the decken theory cannot be held in its present form. These involve a great deal of local detail which can hardly be considered in a review, and trench as well upon the basal concepts of megadiastrophism, which is too large a problem for adequate consideration in a brief reviewing note. In place of the *nappes de recouvrement*, Heritsch follows Ampferer, Schwinner, and others in advocating the *Verschluckungstheorie* which he thinks is free from the objections marshalled against the decken hypothesis.

These interpretations of the structure of the Alps prepare the way for the final chapter, which is a weighing of what are dignified as the two principal theories of mountain making—the contraction theory and the *Verschluckungstheorie*, or hypothesis of insucking or swallowing up. The

time-honored contraction theory (taken in its common form) is attacked by Heritsch upon various grounds. He objects to the conception that the Alps, a narrow zone of 120–200 km., have arisen from the concentrated contraction thrust of the whole earth's crust. He maintains that it is impossible to have a concentration of the contraction in a single line unless there is a shearing of the upper crust over the body of the earth beneath. Rudski is quoted to show that the force necessary to overcome friction is much greater than the crushing strength of the materials, and that the rock sheet therefore should not ride quietly but should break to pieces rather than fold. One must also assume a gathering of strain through a long period of time until it grows up to a mountain-building phase. Schwinner has claimed that this is impossible. Furthermore the movements of the crust, if in consequence of shrinkage of the earth body, must, according to Pfaff, be steady and unbroken. But the facts show the reverse; orogenies are episodic. These and other objections, real or fancied, are urged against the contraction hypothesis.

In preference to the contraction hypothesis, Heritsch gives allegiance to the *Verschluckungstheorie* which is a composite of old and new ideas. The underlying basis for this is the theory of isostasy. The familiar working principle is an irregular distribution of mass reaching down only to 120 km. beneath the surface. Therefore the results of the irregularity (vulcanism and mountain making, according to Schwinner) cannot go deeper. All orogenic and epeirogenic processes would thus be limited to a shallow earth shell—the tectonosphere. Some muddling of ideas enters here, but in the lower zone of the tectonosphere the material is described as flowing with .great internal resistance; i.e., elastic to short period impulses, but yielding to long continued stresses.

The *Verschluckungstheorie* derives its second stimulus from the analogy of cyclonic and anticyclonic movements in meteorology. Through a chain of events in which transfer of heat plays a part, an inflowing whirl or streaming of material (called cyclone) is pictured as occurring in what is termed the "active" portion of the earth body just below the bottom of the "passive" tectonosphere. The material is thought to stream in toward the center of the cyclone and there descend as a part of a larger convection current. By the sucking in toward the depths, broad strips of the surface portion (overlying tectonosphere) would become much too large for the underpinnings and rise out of the depths on shearing planes, one over another, thus developing imbricate structure. The piling over one another of thrust sheets is thus explained on the undercurrent theory by a strong diminution of mass in the depths

whereby large parts of the upper zone also are swallowed. The sliding of the overthrust flakes (gliding hypothesis) is included in the undercurrent theory as a sub-phenomenon.

All of this makes a very pretty theory. Whether, however, a solid globe will permit any such extensive, well-established cyclonic and anticyclonic currents as to allow an analogy with the mobile atmosphere is not so certain. Whether underlying currents streaming in toward a center, or centers, of cyclonic movement can occasion long, linear mountain chains like the Indo-European or Cordilleran chains, which run with little interruption for a quarter of the circumference of the globe, is also not so clear. One may well wonder what is happening to the earth's surface outside of the mountain-forming zones if the surface shell there is being drawn in together above the insucking zone. One might perhaps expect very much more compensatory stretching of the surface above the anticyclones than the geologic evidence will allow. The questions involved in any such fundamental speculation are legion.

The books strikes the reviewer as being rather sparingly illustrated. Its treatment is largely German; very little mention is made of the work of geologists of other nationalities.

R. T. C.

Temperature-Viscosity Relations in the Ternary System, CaO—Al_2O_3—SiO_2. By ALEXANDER L. FEILD and P. H. ROYSTER, United States Bureau of Mines, 1918; Technical Paper 189, pp. 33, pl. 1, figs. 16.

In the course of investigating the composition and properties of blast furnace slags, the authors have determined the temperature-viscosity relations for a part of the ternary system CaO—Al_2O_3—SiO_2. This abstract was prepared to call to the attention of petrologists five points brought out in this paper which are of especial interest to them; particularly in view of the recent discussion by Vogt[1] of viscosity as a factor in the crystallization and genesis of igneous rocks.

1. All the molten silicate mixtures which were the subject of experiment exhibited a rigidity at low shearing stresses under certain limiting values. The reviewer would suggest that herein may, in part, lie the explanation of the oriented growth of crystals under non-uniform pressures in primary gneisses.

2. Only one part of one binary system was investigated, but the authors conclude that in this case: "It would seem that, starting with

[1] J. H. L. Vogt, *Journal of Geology*, Vol. XXXI (1923), pp. 233–52.

either pure component, the isothermal viscosity curve increases first to a maximum and then decreases toward the eutectic."

Isothermal viscosity curves for molten solutions of three components corresponding in composition to the changes in composition of the liquid phase in cooling, with crystallization, from a binary eutectic to a ternary eutectic for the respective components were determined in eight cases. In every case the ternary eutectic showed a maximum viscosity with respect to a minimum at the binary eutectic, or expressed in more general terms, "In each curve the viscosity increases from a minimum at a binary eutectic to a maximum at a quintuple point."

It was further found that not only were the quintuple points for the ternary eutectics reflected as points of maximum viscosity in isothermal viscosity surfaces, but that also the two quintuple points at which α and β calcium orthosilicate and gehlenite are in equilibrium with their melt coincide with pronounced viscosity maxima in profiles of isothermal viscosity surfaces along the calcium orthosilicate-gehlenite boundary curves, even at 1600° C. (The transformation point for α to β calcium orthosilicate is 1420° C. according to Rankin and Wright.[1]) They suggest that the existence of a molecular aggregate identified with the β form is responsible in some way for the excessive viscosity.

Vogt (p. 236) writes, "In short, numerous observations indicate that the viscosity which at a certain temperature characterizes a complex silicate melt such as SiO_2, $KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$, $CaMgSi_2O_6$, etc., may be derived from the viscosity which is characteristic of each of the components. But the viscosity is hardly a linear function of the viscosity of the components." The data presented by Feild and Royster emphasize the latter point. Some of their isothermal viscosity surfaces vary as greatly from a linear function as the melting (temperature-concentration) surfaces for mixed components. For example, at 1400° C. the binary eutectic of anorthite and gehlenite has a viscosity of 4, the binary eutectic of anorthite and calcium metasilicate a viscosity of 10, and the binary eutectic of gehlenite and calcium metasilicate a viscosity of 5; yet the viscosity of the ternary eutectic at the same temperature for these three components (gehlenite, calcium metasilicate, and anorthite) is about 62.

3. The compounds investigated exist as such in the liquid state. The isothermal viscosity surfaces are so closely correlated with the stability fields of the compounds as previously determined by Rankin and Wright using the "quenching method" (temperature-concentration) that the

[1] G. A. Rankin and F. E. Wright, "The Ternary System CaO–Al_2O_3–SiO_2," *American Journal of Science*, Vol. XXXIX (1915), p. 7.

authors are inclined to believe that by measurements of the viscosity of these silicates in the liquid state alone it would be possible to establish the existence of the compounds within the ternary system and to determine more or less closely their stability fields. Hence their conclusion that "If from the measurement of a physical property of a liquid the field of stability of a compound can be determined, it follows inevitably that the compound exists as such in the liquid state."

4. The viscosity is directly dependent upon the relative proportions of the "compounds" present in the liquid melt, and it is futile to search for a general relation between the viscosity and the composition as expressed in terms of the component oxides.

5. Data are given and discussed which illustrate the considerable differences in the temperature coefficient of viscosities for mixtures of different composition.

The authors are well justified in pointing out the importance of their data and conclusions for certain geological problems. The imperative need for additional data on the viscosities of mixtures of solid solutions, etc., is self-evident.

A. F. BUDDINGTON

PRINCETON UNIVERSITY

Lehrbuch der Geologie, II Teil: Grundzüge der historischen Geologie. By F. X. SCHAFFER. Leipzig and Vienna: Franz Deuticke, 1924. Pp. xi+628.

This textbook has one outstanding feature. It summarizes the known historical geology of the world, rather than that of Europe or North America or some other minor fraction of the earth's surface.

The book is abundantly and judiciously illustrated.

A. O. WOODFORD.

Mining Review for the Half-Year ended December 31st, 1922, No. 37. South Australia Department of Mines. Compiled by LIONEL C. E. GEE. Adelaide: R. E. E. Rogers, Government Printer, North Terrace. 1923.

Contains table showing the mineral production of South Australia for the years 1837 to 1922 (inclusive), so far as can be ascertained.

E. S. B.

Scientific Survey of Porto Rico and the Virgin Islands, Volume II, Part 1, The Geology of the Lares District, Porto Rico. By BELA HUBBARD. New York Academy of Sciences, New York, 1923.